第 20 卷第 4 期
2022 年 8 月
动 力 学 与 控 制 学 报
JOURNAL OF DYNAMICS AND CONTROL
Vol. 20 No. 4
Aug. 2022

文章编号:1672-6553-2022-20(4)-012-12
DOI:10.6052/1672-6553-2021-XXX

流致振动压电能量俘获的研究进展*

绳丽洁　王军雷†
(郑州大学 机械与动力工程学院,郑州　450001)

摘要　流致振动是典型的流固耦合现象,其引起的周期性作用力会使结构发生疲劳损坏从而引发安全性问题,故在工程中备受关注. 近年来,随着振动俘能技术的发展以及微电子、无线网络和微机电系统等低能耗产品的发展应用,基于流致振动的俘能技术受到了广泛关注,然而流致振动研究方面仍存在较多问题亟待解决. 本文对目前现有的流致振动俘能技术的发展现状进行了综述,讨论了几种提高流致振动俘能装置效率的措施. 最后,总结了流致振动俘能领域目前存在的问题和挑战,提出了对未来流致振动能量收集发展的展望.

关键词　流致振动,　涡激振动,　驰振,　俘能技术
中图分类号:TM619　**文献标志码:**A

引言

近年来,石油、煤炭等化石燃料的燃烧造成了严重的环境问题. 同时,化石能源日益枯竭,能源短缺问题恶化,使可再生能源的开发和利用得到了密切关注. 目前,随着无线传感器网络(wireless sensor network,WSNs)、微机电系统(micro-electro-mechanical system,MEMS)和无人机(wnmanned aerial vehicle,UAV)等技术飞速发展,微电子产品自供能技术的开发问题亟待解决. 传统电池存在容量有限、寿命较短、更换回收成本高、续航问题严重及环境污染等问题[1],环境能量俘获技术因其可从环境中获取可再生能源并为电子元件进行供电,受到研究者广泛关注.

流体流经结构时会产生周期性激振力并诱发结构产生振动,被称为流致振动(flow-induced vibration,FIV)[2]. 流致振动俘能技术可以采集环境中的流体动能,在土木工程、风能工程和海洋工程等领域获得了广泛关注. 从环境中收集流体动能并将其进一步转化为机械能和电能可以为自供能技术提供有利支持. 因此探索流致振动能量俘获机理,设计并优化流致振动俘能系统,具有重要学术价值和工程实际意义.

能量转换存在多种机制,常见的俘能系统根据机理不同可分为电磁式[3,4]、静电式[5,6]、摩擦电式[7-9]和压电式[10-13]. 电磁式是利用线圈切割磁感线的原理. 静电式的关键部件是可变电容器,它通过改变电容将机械运动的能量转化为电能[14]. 摩擦电式俘能装置的原理是两种电负性不同的材料之间相接触而引起电子的转移,当接触面发生分离时,器件会产生交流电输出[15]. 压电式俘能装置是通过材料发生机械形变产生电荷并通过振动载荷以产生交变电压. 压电式俘能装置所俘获的电能可以与微机电系统实现较好的融合,同时具备体积小、结构简单、对工作环境要求低、无热效应、所采集的能量密度高、不受电磁波影响等优点[16],因此受到较多研究者关注.

较低流速的流致振动通常指涡激振动和驰振. 其中,涡激振动是由流体流经结构表面时产生的旋涡脱落引起的周期性结构振动[2]. 当钝体的涡激振动频率与其固有频率接近时,存在一种特殊的“频率锁定(lock-in) 现象[17,18]. 当系统发生锁振时,振幅随流速增大,但频率保持不变. 涡激振动按振幅大小及频率锁定情况分为初始分支、上分支和下分

2021-07-15 收到第 1 稿,2021-08-12 收到修改稿.
* 国家自然科学基金资助项目(51977196)
† 通信作者 E-mail:jlwang@ zzu. edu. cn

支. 涡激振动的“锁定”现象往往会对工程结构的安全产生不利影响,因而需要被抑制或消除. 然而利用其振幅大、频率稳定的特点,流致振动俘能装置(flow-induced vibration energy harvester, FIVEH)的设计近年来得到快速发展. Bernitsas 等[19]首次提出涡激振动海洋清洁能源系统(vortex-induced vibration aquatic clean energy, VIVACE),基于涡激振动原理将潮汐能转化为振动能,再通过电磁感应机制将振动能转化为电能. 驰振通常包括垂直于来流方向的横风向驰振和扭转驰振两种,是一种发散性自激振动[2]. 驰振是一种典型的发散性自激振动,其产生原因是升力随攻角曲线具有负斜率,从而使系统产生负阻尼,进而导致结构从外界持续吸收能量并产生发散性振动. 研究者对基于驰振的流致振动俘能系统也进行了研究,如 Barrero 等[20]对基于驰振能量采集的可能性进行了分析,并提出其数学模型. 基于驰振的理论模型,建立了质量和机械能、横截面的几何形状、流速以及能量效率之间的关系.

研究表明,从涡激振动和驰振中获取振动能量的方式具有可行性[21,22]. 为了加强流致振动、提高能量采集的性能,研究者们进行了一系列的探索,设计了大量的新型流致振动俘能装置. 本文第 1 节介绍了在钝体表面加装附着装置[23]的流致振动俘能研究. 通过在钝体表面放置粗糙带、小尺寸杆状附件、分隔板等附件以优化俘能装置的性能. 第 2 节介绍了通过钝体组合或改变钝体的形状以实现涡-驰耦合振动的俘能装置,从而将两种振动的优势结合起来. 第 3 节通过引入非线性磁力[24-27]来提高俘能装置的采集性能和实际环境中的适用性. 第 4 节基于等效电路的方法研究了复杂电路接口对俘能装置的影响. 第 5 节提出了目前流致振动俘能技术存在的问题与挑战. 第 6 节对本文进行了总结,提出了对未来流致振动能量收集发展的展望. 本文旨在对流致振动俘能技术的现状进行综述,为后续流致振动俘能装置的研发提供一定参考.

1　钝体表面加装附着装置

由于钝体结构表面的粗糙性、附着物等会对其承受空气绕流时的气动力响应产生影响,因此,研究者展开了在钝体表面放置附属结构或装置的研究. 例如在圆柱表面装备附属物来控制流致振动,这种方法称为被动湍流控制(passive turbulence control, PTC)[28]. Ding 等[28]在圆柱体前侧表面对称连接两个粗糙带,通过计算流体动力学(computational fluid dynamic, CFD)和实验的方法对 PTC 俘能装置进行研究,如图 1 所示. 结果发现,PTC 可显著提高涡激振动水生清洁能源的振动响应和俘能效率. 基于上述研究,章大海等[29]对放置非对称粗糙带的单圆柱流致振动进行了数值模拟. 结果表明:与放置对称粗糙带的圆柱相比,带有非对称粗糙带圆柱的俘能装置在涡激振动上分支有更大的输出功率. 但是,上述研究仅考虑了粗糙带在固定安装角度对能量收集器的影响,事实上,不同的安装位置将带来不同的影响. Wang 等[30]系统地研究了连接在钝体表面上不同厚度和放置角度的粗糙带对涡激振动振幅和输出功率的影响. 结果显示:在钝体表面放置 $W = 8\mathrm{mm}$(宽度)、$\theta = 60^\circ$(θ 表示从前驻点测量的周向位置)的粗糙带,可显著扩大圆柱的共振区间,并提高输出功率. 然而,该研究只针对粗糙带的安装位置和厚度进行研究,并未讨论粗糙带的形状对钝体表面气动力的影响. Zhu 等[31]采用双向流固耦合的方法研究了高雷诺数下粗糙带的安装角度和形状对圆柱体俘能器的影响. 从湍流强度、旋涡脱落模式和尾迹宽度的变化可以看出,振动响应由涡激振动向驰振转变,大幅提高了能量收集性能. 此外,研究者对于带有小尺寸杆状附件俘能装置的性能也进行了研究. Wang 等[32]提出了一种带有两个小直径圆柱杆的圆柱钝体俘能装置,并对该装置进行了CFD数值模拟,

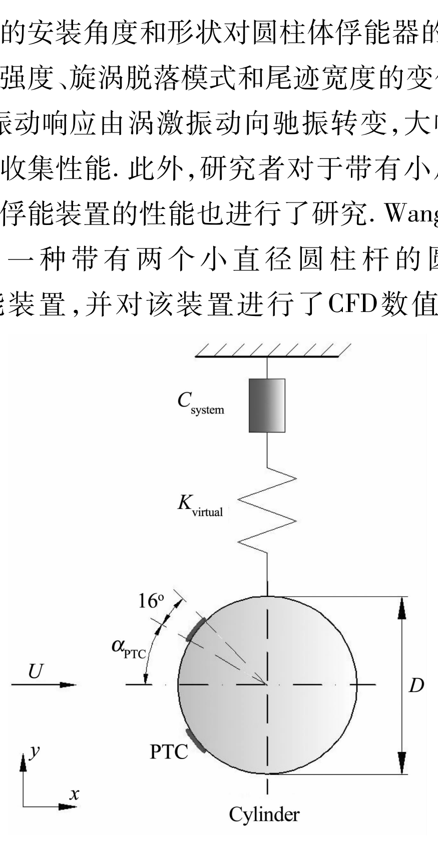


图 1　清洁能源涡激振动采集器的物理模型示意图
Fig. 1　Sketch of the physical model of the VIVACE converter

CFD 网格如图 2(a－b)所示. 在计算雷诺数范围内,小圆柱杆放置在圆柱钝体上的角度为 55°～65°的范围内都具有良好的能量采集性能. 通常,有尖角的附件更容易增强振动[33]. Hu 等[34]比较了三种不同横截面形状(圆形、三角形和正方形)的杆状附件在不同放置角度对俘能装置性能的影响效果,如图 3(a－b)所示. 其中安装在 $\theta=60°$的三角形杆圆柱风能采集器的性能最优.

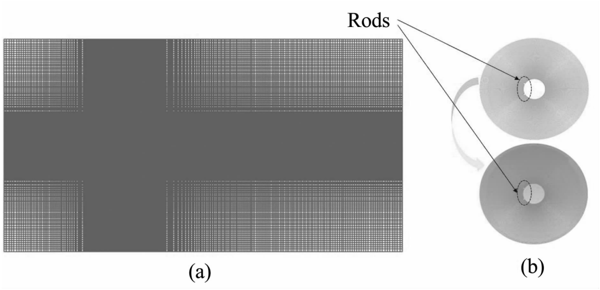


图 2　(a)背景网格;(b)重叠网格

Fig. 2　(a) Background grid;(b) overset grid

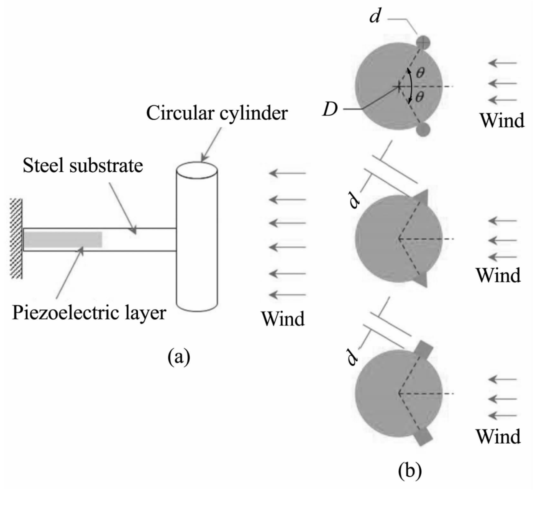


图 3　连接不同截面杆的圆柱风能采集器:(a)基于光滑圆柱的风能采集器;(b)连接在主圆柱上的三个不同形状(圆形、等边三角形和正方形)附杆

Fig. 3　Circular cylinder-based wind energy harvester with different types of rods attached to the main circular cylinder:(a) circular cylinder－based wind energy harvester;(b) three different shaped (circle, equilateral triangle and square) rods attached on the main circular cylinder

近年来,研究者致力在钝体上安装分隔板,以提高能量收集性能. 例如,对于基于圆柱钝体的能量采集器,首先研究了分隔板的长度对能量采集器性能的影响. Song 等[35]指出,在圆柱尾迹附近放置分隔板可以改善风致振动压电能量采集器的性能. 研究结果发现:长度为 0.65D(D 为圆柱的直径)的分隔板是提高采集性能的最佳长度. 随后,探讨了分隔板安装角度对能量采集器性能的影响. Wang 等[36]设计了一种带有两个分隔板的压电能量采集装置,研究了不同的安装角度对其性能的影响,如图 4(a－d)所示. 结果表明:对于放置角度为 30°、60°和 180°的情况,振动响应从涡激振动过渡到驰振,与不带分隔板相比,最大输出电压分别提高了 67.93%、188.61% 和 77.22%. 此外,Noel 等[37]研究了在方柱末端添加一个刚性分隔板对方柱周围流体的影响. 研究发现:添加分隔板后方柱的输出功率提高了 67%.

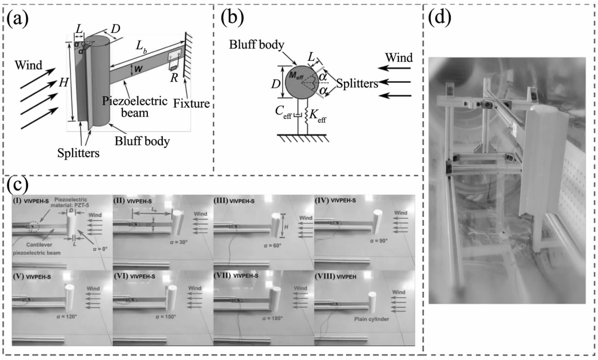


图 4　带分隔板的基于涡激振动压电能量采集器的结构:(a)原型的三维示意图;(b)等效二维系统的示意图;(c)不同分隔板安装角度 α 的涡激振动装置和常规涡激振动装置;(d)风洞中的涡激振动装置

Fig. 4　Configuration of VIVPEH with splitters:(a) the 3D schematic of the prototype;(b) the schematic of the equivalent 2D system;(c) the prototypes of VIVPEH-S with different angles α and the conventional VIVPEH;(d) the VIVPEH-S set-up installed in the wind tunnel

除此这些常规附件以外,还有一些特殊形状附件. Wang 等[23]将一种"Y 形"结构附加在圆柱钝体上,得到了一种新型的高性能压电风能采集器,如图 5(a－b)所示. 该结构附加在钝体上可使涡激振动向驰振转变,有效提高能量采集性能. 基于上述研究的启发,Ding 等[38]研究了在圆柱钝体上附加鳍状条带对俘能装置的输出功率影响. 其中,当放置角度在 30°～60°范围内时,最大功率可达光滑圆柱体的 25.5 倍. 近年来,一些研究者将周期性超表面引入流致振动俘能装置的钝体设计中. Wang 等[39]首次将超表面结构与流致振动能量收集相结合,设计了四种周期性超表面(凸半球、凸三棱柱、凸圆柱和凸方柱),研究其对于涡激振动的影响,如图 6 所示. 研究发现:具有凸三棱柱和凸半球表面的钝体可以通过增大锁定区域来增强涡激振动的响应,CFD 模拟结果如图 7(a－c)所示. 其中,具有凸半球表面的钝体与光滑表面的钝体相比,锁定区域增加了 63.64%.

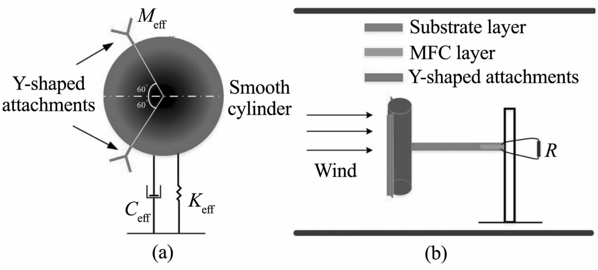


图 5　GPEH-Y 示意图:(a)等效示意图;(b)风洞实验中的物理图

Fig. 5　Schematic diagrams of the GPEH-Y:(a) equivalent schematic diagram;(b) physical diagram in the wind tunnel test

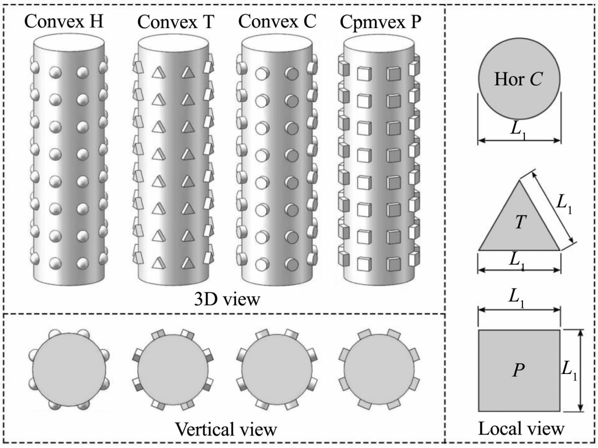


图 6　具有不同周期性超表面的钝体

Fig. 6　The bluff bodies decorated by various metasurface patterns

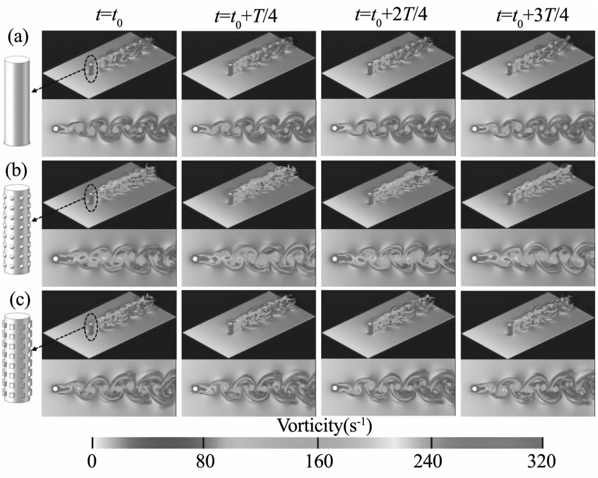


图 7　通过 CFD 模拟得到的涡度等值线以说明旋涡脱落过程:(a)普通圆柱钝体;(b)具有凸半球型表面的钝体;(c)具有凸方柱型表面的钝体

Fig. 7　Vorticity contours obtained from CFD simulation to illustrate the vortex shedding processes around:(a) the ordinary cylinder bluff body;(b) the bluff body decorated by convex H pattern;(c) the bluff body decorated by convex P pattern

2　涡 - 驰耦合振动俘能装置

涡激振动与驰振的相互作用可以显著降低风电场的工作风速,以拓宽有效的工作范围,提高较高风速下的电压输出. 周帅等[40]通过对 3 个大长细比钝体构件的工程实例进行数值模拟和风洞实验,证实了在一定条件下构件发生涡 - 驰耦合振动的可能性. 在此基础上,Yang 等[41]对涡 - 驰耦合振动下的压电俘能装置进行了建模,并用实验验证了所提出的分布参数机电耦合模型,以优化涡 - 驰耦合压电风能采集装置. 随后,Yang 等[42]研究了涡 - 驰耦合作用下空气动力学参数对压电风能采集器性能的影响,在结果中观察到了有利于提高输出电压的驼峰现象. He 等[43]通过风洞实验对涡-驰耦合现象进行了研究,实验证明,通过改变钝体的几何形状,可以分别实现驰振、涡激振动及涡 - 驰耦合振动. 为了实现涡 - 驰耦合振动,研究者将常规钝体组合放置,Qin 等[44]提出了由一个十字形悬臂梁和两个方柱及一个圆柱组成的新型风能采集器,并在系统中增加一个尖端磁铁和两个固定磁铁,如图 8 所示. 结果表明:该装置可以结合涡激振动和驰振的优势,提高风能的采集效率,在 2.0 ~ 7.0 m/s 的风速范围内提供较大的输出.

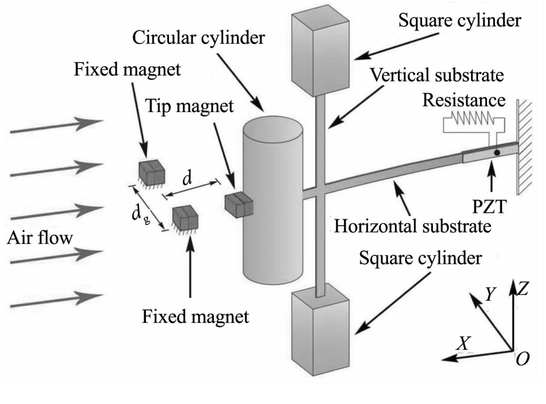


图 8　基于涡激振动和驰振的双稳态压电能量采集器原理图

Fig. 8　The schematic diagram of the BPEH based on vortex-induced vibration and galloping

此外,研究者将一些常规钝体结构组合成新钝体. Wang 等[45]通过风洞试验,对不同尺寸和安装方向的纺锤形及蝴蝶形钝体的俘能装置性能进行研究,如图 9(a - d)所示. 与传统的基于驰振的能量采集器相比,由于耦合振动的存在,具有最小宽度比的垂直纺锤形钝体可以将压电能量采集器的临界风速降低 13% 以上,并将最大电压输出提高 160% 以上. Sun 等[46]研究了球形钝体(由两个相同截面的半方柱和半圆柱组成)的涡 - 驰耦合效应. 实验结果表明:在低风速内,球形钝体的平均输

出功率比方柱增加了 75%，最大功率提高了 193%. Wang 等[47]对不同攻角下的三种圆形和方形截面组合的俘能装置的性能进行理论、实验和 CFD 研究，如图 10 所示. 研究表明：对于某些特定攻角和横截面组合，压电风能采集器能够将涡激振动和驰振的优点结合起来. Yang 等[48]提出了一种新型的风能采集器，该采集器在 3/4 圆柱和 1/4 方柱的组合钝体中添加了两个磁体，以构成单稳态涡-驰耦合风能采集器. 如图 11(a-b)所示，与线性采集器相比，单稳态采集器工作风速范围更宽，输出电压更高，性能更好，且磁体距离对于该装置的性能存在较大影响.

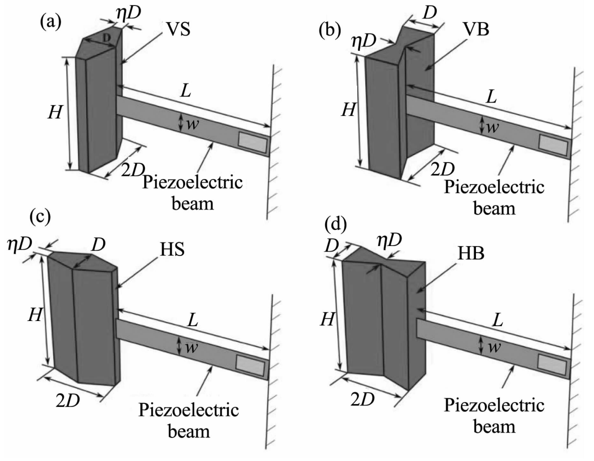


图 9 压电式风能采集器三维结构示意图：(a)垂直纺锤形(VS)；(b)垂直蝴蝶形(VB)；(c)水平纺锤形(HS)；(d)水平蝴蝶形(HB)

Fig. 9 The 3D schematics of the proposed piezoelectric wind energy harvester with (a) vertical spindle-like (VS); (b) vertical butterfly-like (VB); (c) horizontal spindle-like (HS) and (d) horizontal butterfly-like bluff bodies (HB)

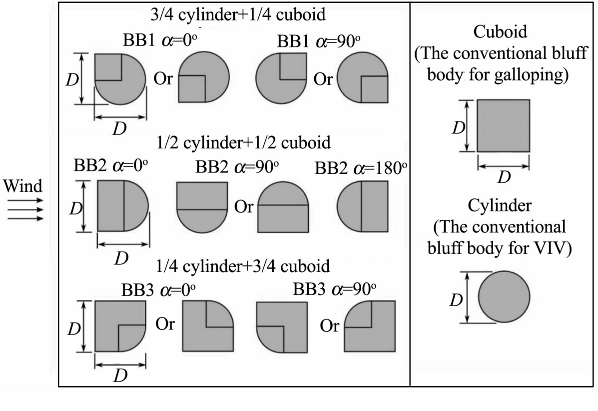
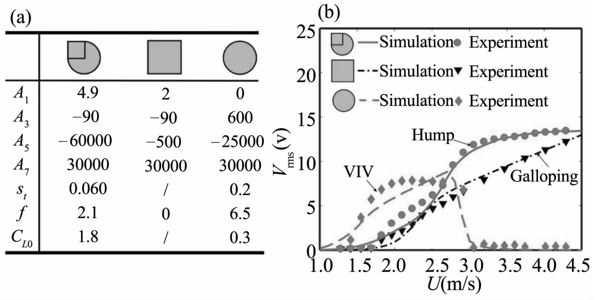


图 10 实验情况示意图：不同横截面的钝体和不同攻角

Fig. 10 The schematic of the test cases: different cross-sectioned bluff bodies and different wind attack angles



	◔	■	●
A_1	4.9	2	0
A_3	−90	−90	600
A_5	−60000	−500	−25000
A_7	30000	30000	30000
s_t	0.060	/	0.2
f	2.1	0	6.5
C_{L0}	1.8	/	0.3

图 11 (a)空气动力学参数；(b)结果比较

Fig. 11 (a) The identified aerodynamic parameters for simulation; (b) comparative results

3 非线性流致振动俘能装置

一些研究者将非线性磁力引入俘能装置来提高采集性能和实际环境中的适用性，并对具有单稳态、双稳态[49,50]和三稳态[51,52]，硬化和软化特性[53]的非线性俘能装置进行了的研究. Stanton[54]，Erturk 和 Inman 等[55]研究了带有非线性磁场结构的双稳态俘能装置的大振幅周期振荡. 通过双稳态结构可以有效提升振动俘能器的工作带宽，提升俘能效率. 与双稳态的俘能装置相比，三稳态俘能装置具有三个稳定平衡位置和两个不稳定平衡位置. Li 等[56]提出了一种三稳态俘能装置，该装置可以在低频基础激励下实现阱间振荡，并通过三稳态相干共振获得较高的能量采集效率. 基于上述研究，研究者对流致振动环境下的振动俘能装置进行探索. Naseer 等[57]提出通过引入非线性磁力来提高涡激振动俘能装置的性能，并设计一种单稳态结构涡激振动压电俘能装置，通过仿真证实了单稳态结构对工作带宽和效率的改善. 对于双稳态非线性流致振动俘能装置，Alhadidi 和 Daqaq[58]提出了一种具有双稳态特性的尾流驰振俘能装置，该装置与线性设计相比，双稳态结构可以显著提高系统的工作带宽. Bibo 等[53]提出了一种具有二次势能函数的驰振压电俘能装置，研究非线性恢复力对流致振动俘能装置性能的影响，如图 12 所示. 结果表明：与其他装置相比，系统大幅运动时双稳态俘能装置的性能最优. Zhang 等[59]提出在悬臂梁式压电俘能装置中添加一对互斥磁体，从而形成双稳态结构. 研究发现：在非线性磁场力作用下，俘能效率提高了 29%，锁频范围拓宽了 138%. Yang 等[60]提出了一种双梁压磁风能采集装置，如图 13(a-c)所示. 风洞实验结果表明：与线性双梁压电风能采集装置相

比,该装置的临界风速降低了 41.9%. 同时,Wang 等[61]也进行了类似的研究,分别在低、中、高风速区间发现了阱内振荡、混沌振荡和阱间振荡. 研究发现:减小梁刚度比、选择合适的有效质量比及增加钝体宽度,可以提高双梁压磁风能采集装置的性能. 胡晨阳等[60]提出了一种改进的双稳态涡激振动俘能装置,通过数值仿真探究了磁铁间距对系统性能的影响. 研究结果显示:磁距较大时,输出功率变大;磁距较小时,功率减小且起振速度也减小. 这种现象与势垒的高度变化有关.

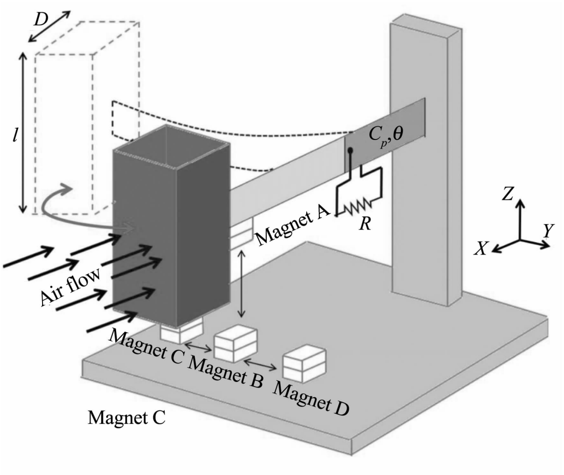


图 12　非线性驰振流动能量采集器示意图
Fig. 12　A schematic diagram of the galloping non-linear FEH

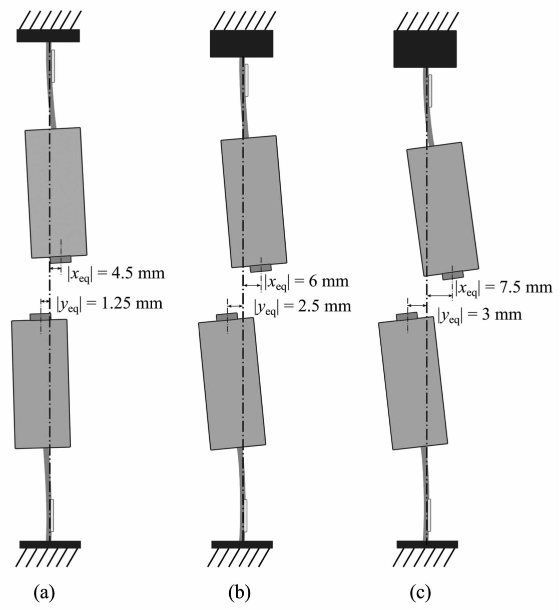


图 13　磁铁间相互作用使梁弯曲简图:
(a) $\Delta = 18$mm;(b) $\Delta = 12$mm;(c) $\Delta = 6$mm
Fig. 13　The schematics of the beam buckled by the magnetic interaction: (a) $\Delta = 18$ mm; (b) $\Delta = 12$ mm; (c) $\Delta = 6$ mm

对于三稳态俘能装置,Zhou 等[63]建立了带有非线性磁力的三稳态俘能装置的机电耦合模型,并描述了其动态特性,如图 14(a-b)所示. 实验证明:三稳态振荡装置的等效非线性力为高次多项式,且与双稳态俘能装置相比,三稳态俘能装置能够在更宽的低频范围内收集能量. 同时,Zhou 等[64]设计了一种三稳态压电俘能装置. 结果表明:三稳态压电俘能装置可在较宽的频率范围(15.1-32.5Hz)内获取振动能量. Zhou 等[65]提出了一种三稳态涡激振动俘能装置,并建立了其数学模型. 与线性装置相比,该装置的输出电压更高,工作范围更宽. 谭红波等[66]比较了双稳态和三稳态驰振能量收集装置的动力学特性和发电性能,利用数值仿真证明了在较低流速下三稳态系统的发电性能更好. Wang 等[67]对三稳态驰振俘能装置进行参数研究,探讨了三稳态振动系统的势能与动能的转换机理,如图 15(a-b)所示. 结果表明:与线性驰振压电俘能装置相比,该装置的临界风速降低了 33%.

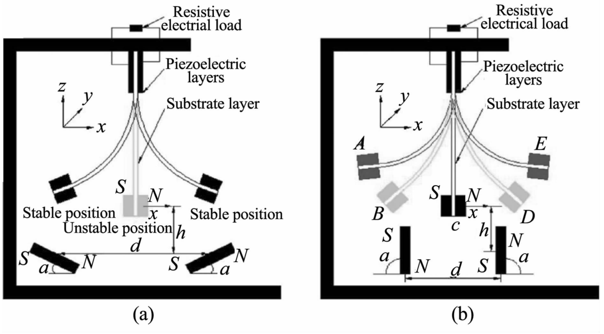


图 14　非线性能量收集示意图:(a)双稳态;(b)三稳态
Fig. 14　Non-linear energy harvesting schematics
(a) bistable; (b) tristable

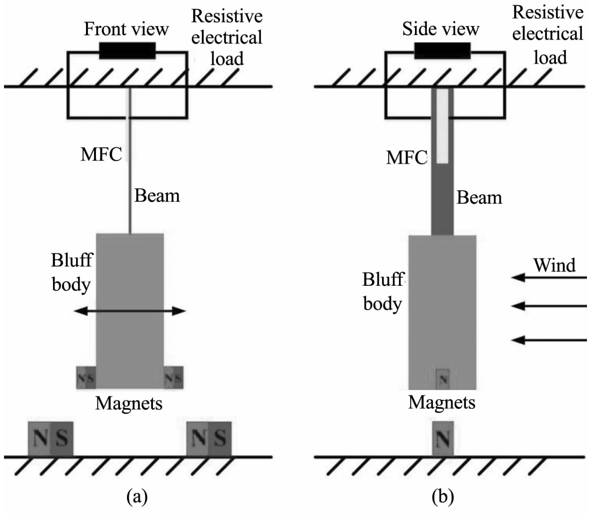


图 15　基于三稳态驰振的压电能量采集器示意图:
(a)正视图;(b)侧视图
Fig. 15　Schematic of the TGPEH:
(a) front view; (b) side view

表1总结了前三节提到的部分流致振动能量收集装置性能改善的表现.

4 基于等效电路法的俘能装置设计

为研究复杂电路接口对俘能装置的影响,研究者基于等效电路(equivalent circuit method, ECM)的方法建立了其电路模型,对不同结构参数下和外界电路下的压电振动俘能装置的性能以及影响因素进行研究. Yang 和 Tang[68]使用等效电路法对基础激励下的压电振动能量采集系统进行了建模和实验,有效解决直流电路元件无法直接数学建模的问题. Tang 等[69]提出了复杂电路的驰振俘能系统的等效电路模型,如图16所示. 结果表明:交流接口的最大临界风速大于直流接口. Zhao 等[70]比较了四种驰振风能采集接口电路的性能,提出了不同情况下的电路选择方法. Zhao 等[71]还对驰振俘能装置的动力学特性进行了研究,采用电感同步开关电路以增强采集性能. 在风力条件和输出功率要求相同的情况下,与连接标准电路的系统相比,该系统风能利用率得到提升. 王定标等[72]建立了基于驰振的变三角截面压电俘能装置的等效电路,研究了外接电路、钝体角和来流速度等对变三角截面驰振压电俘能装置采集性能的影响. 靳遵龙等[73]对PTC圆柱驰振俘能等效电路进行了研究,分析了临界风速随负载的变化规律和不同风速、负载对性能的影响. Wang 等[74]提出了一种涡激振动等效电路模型,比较了具有交流和直流接口的涡激振动俘能装置的性能. 对于引入非线性磁力的俘能装置, Lan 等[75]研究了直流电路和交流电路接口对非线性压电俘能装置的影响,如图17所示. 结果显示:与线性装置相比,两种接口电路对单稳态压电俘能装置的功率峰值偏移和工作带宽均会产生影响.

表1 流致振动俘能装置的研究总结

Table 1 Research summary of research on flow-induced vibration energy harvester

sort	research content	working bandwidth	Flow-induced vibration performance improves performance
additional attachment device on the surface of the blunt body	energy harvesting device with partition plate when $\alpha=60°$[36]	≥1.82 m/s	maximum output voltage increased by 188.61%
	energy harvesting device with additional fin-shaped strips[38]	≥3.0 m/s	the maximum power can reach 25.5 times that of a smooth cylinder
	energy harvesting device with bluff body with convex hemispherical super surface[39]	1.413 ~ 3.3879 m/s	the locked area is increased by 63.64% compared to smooth and blunt bodies
hybrid wind energy scavenging by coupling vortex-induced vibrations and galloping	the piezoelectric wind energy harvester with vertical spindle-like bluff body[45]	≥1.69 m/s	maximum voltage output increased by more than 160%
	"BB1 $\alpha=0°$" mode in combination of circular and square cross-sections[46]	1.0 ~ 4.5 m/s	the maximum voltage is 71.34% higher than that of vortex-induced vibration
non-linear flow-induced vibration energy harvesting device	cantilever beam type piezoelectric energy harvesting device with a pair of mutually exclusive magnets[59]	2.0 ~ 3.9 m/s	the energy capture efficiency has been increased by 29%, and the frequency lock range has been expanded by 138%
	double-beam piezomagnetic wind energy harvesting device[60]	1.8 ~ 3.9 m/s	compared with linear, the critical wind speed is reduced by 41.9%
	three-stable galloping energy harvesting device[67]	≥1.0 m/s	the maximum output power is increased by 35.3% compared with linear

5 问题与挑战

近二十年,国内外研究者围绕流致振动俘能进行了大量的机理和实验研究,并取得了重要进展,然而通过对前人研究成果进行总结可以发现,虽然目前流致振动俘能技术的应用前景良好,但由于外界环境的多变性和内部机理的复杂性,在实际应用中,仍存在以下困难和挑战亟待解决.

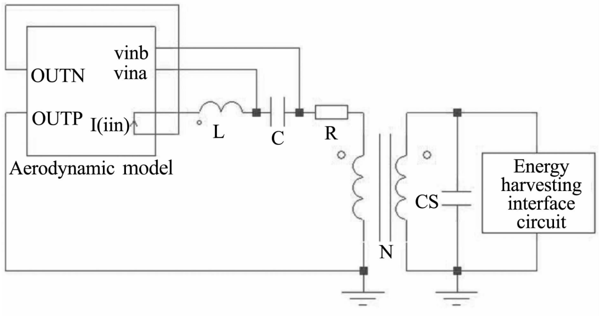


图 16　驰振压电能量采集系统的等效电路图
Fig. 16　Equivalent circuit representation of GPEH system

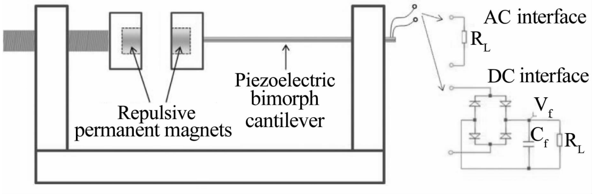


图 17　连接到交流或直流接口电路的单稳态压电能量采集器原理图
Fig. 17　Schematic of monostable PEH connected to AC or DC interface circuit

(1) 复杂流场下流致振动俘能理论尚未成熟,复杂钝体表面周围的流动机理仍需进一步深入研究.

(2) 如何进一步提高现有流致振动俘能装置的性能,如拓宽工作带宽、提高输出功率等仍是重大挑战.

(3) 流致振动俘能技术仍处于理论研究阶段.与理想的风洞条件相比,流致振动俘能装置的实际应用不仅要考虑能量采集的效率,还要考虑设备的成本,以及设备的维护、寿命等因素.

6　结论与展望

流致振动俘能技术具有良好的应用前景,对于微机电功能系统、无线传感网络、嵌入式监测系统,检联网 (Internet of Things,IOT) 等微小型低功率设备,可满足其供电需求.本文综述了现有流致振动俘能技术以及各种提高俘能性能的措施,具体包括对在钝体上外加可拆卸附件、改变钝体形状、引入非线性磁力和等效电路模型方法等.随着新材料和相关测试技术的发展,今后还有一些提高流致振动俘能装置性能、降低经济成本的方法等待研究人员的探索.

传统研究方法如风洞实验和 CFD 数值计算耗时较长、成本较高.机器学习(machine learning)技术可作为一种有效且经济的替代方法对流致振动能量采集中的流动现象进行研究.例如,Zhang 等[76]通过风洞实验获得了大量原始数据集,并利用机器学习技术训练两个回归模型,分别预测了尾流驰振压电能量采集器的均方根电压和最大位移.机器学习目前在流致振动俘能技术中的应用尚未成熟,在今后可以以实验和数值计算数据为基础,通过机器学习识别和预测能量采集器输出响应并进一步提高系统能量采集效率.

此外,研究者已经将周期性超表面应用到流致振动能量采集器中,但现阶段的研究尚未成熟.下一步可以对基于周期性超表面流致振动的能量采集器进行进一步地优化,提高俘能效率.

最后,在现阶段,风能采集技术仍然局限于实验室研究阶段,风能采集器在解决实际工程问题方面还不成熟.其主要问题在于由能量采集技术支持的电源不如化学电池的电源稳定,流致振动俘能系统的鲁棒性需要进一步提升.

参　考　文　献

1　Paradiso J A, Starner T. Energy scavenging for mobile and wireless electronics. *IEEE Pervasive Computing*, 2005, 4(1):18 ~ 27

2　Blevins R D, Saunders H. Flow-induced vibration. *Journal of Mechanical Design*, 1977

3　Bo L D, Gardonio P, Turco E. Analysis and scaling study of vibration energy harvesting with reactive electromagnetic and piezoelectric transducers. *Journal of Sound and Vibration*, 2020, 484: 115510

4　刘仲琳,冷永刚,刘进军,等.双稳悬臂梁电磁式振动能量采集研究.振动与冲击, 2019, 38(23):126 ~ 133 (Liu Z L ,Leng Y G ,Liu J J, et al. Electromagnetic type vibration energy harvester based on bi-stable cantilever beam. *Journal of Vibration and Shock*, 2019, 38 (23):126 ~ 133(in Chinese))

5　Mitcheson P D, Miao P, Stark B H, et al. MEMS electrostatic micropower generator for low frequency operation. *Sensors & Actuators A Physical*, 2004, 115(2-3): 523 ~ 529

6　Khan F U, Qadir M U. State-of-the-art in vibration-based electrostatic energy harvesting. *Journal of Micromechanics and Microengineering*, 2016, 26(10):103001

7　Ronan H, Hong-Joon Y, Hanjun R, et al. Transcutaneous ultrasound energy harvesting using capacitive triboelectric technology. *Science*, 2019, 365(6452):491 ~ 494

8 Khan U, Kim S W. Triboelectric Nanogenerators for Blue Energy Harvesting. *ACS Nano*, 2016, 10(7):6429 ~ 6432

9 胡鑫,黄博,唐刚,等. 一种悬臂梁式摩擦宽频振动能量采集器的研究. 南昌工程学院学报, 2020, 39(1): 80 ~ 85(Hu X, Huang B, Tang G, et al. Analysis of broadband vibration triboelectric energy harvester based on cantilever beam. *Journal of Nanchang Institute of Technology*, 2020, 39(1):80 ~ 85(in Chinese))

10 曹东兴,吴鹏,张伟,等. 一种新型压电俘能器的振动特性分析及性能研究. 动力学与控制学报, 2015, 13(4):300 ~ 307(Cao D X, Wu P, Zhang W, et al. Nonlinear vibration of a novel piezoelectric vibration energy harvester. *Journal of Dynamics and Control*, 2015, 13(4):300 ~ 307(in Chinese))

11 石朝成,李响,袁天辰,等. 双梁磁力压电振动能量采集器的实验和仿真. 动力学与控制学报, 2017, 15(1): 68 ~ 68(Shi C C, Li X, Yuan T C, et al. Experimental and numerical research on a double-beam magnetic vibration piezoelectric energy harvester. *Journal of Dynamics and Control*, 2017, 15(1):68 ~ 68(in Chinese))

12 董璇,王保志,张成功,等. MEMS压电能量采集器的研究进展. 微纳电子技术,2021,58(4):279 ~ 291(Dong X, Wang B Z, Zhang C G, et al. Research progress of MEMS piezoelectric energy harvesters. *Micronanoelectronic Technology*,2021,58(4):279 ~ 291(in Chinese))

13 Hu G B, Wang J L, Tang L H. A comb-like beam based piezoelectric system for galloping energy harvesting. *Mechanical Systems and Signal Processing*, 2021, 150: 107301

14 Dragunov V P, Ostertak D I, Pelmenev K G, et al. Electrostatic vibrational energy converter with two variable capacitors. *Sensors and Actuators A Physical*, 2020, 318: 112501

15 韩昌报,王嫚琪,黄建华,等. 摩擦纳米发电技术研究进展及其潜在应用. 北京工业大学学报, 2020, 46(10):1103 ~ 1127(Han C B, Wang M Q, Huang J H, et al. Research progress of triboelectric generator and its potential application. *Journal of Beijing University of Technology*, 2020, 46(10):1103 ~ 1127 (in Chinese))

16 袁江波,谢涛,单小彪,等. 压电俘能技术研究现状综述. 振动与冲击,2009,28(10):36 ~ 41(Yuan J B, Xie T, Chen W S, et al. A review of current situation for piezoelectric energy harvesting. *Journal of Vibration and Shock*,2009,28(10):36 ~ 41(in Chinese))

17 Zou Q F, Ding L, Wang H B, et al. Two-degree-of-freedom flow-induced vibration of a rotating circular cylinder. *Ocean Engineering*, 2019, 191:106505

18 Zhu H J, Li G M, Wang J L. Flow-induced vibration of a circular cylinder with splitter plates placed upstream and downstream individually and simultaneously. *Applied Ocean Research*, 2020, 97:102084

19 Bernitsas M M, Raghavan K, Ben-Simon Y, et al. VIVACE (Vortex Induced Vibration Aquatic Clean Energy): A new concept in generation of clean and renewable energy from fluid flow. *Journal of Offshore Mechanics and Arctic Engineering*, 2008, 130(4):041101-1 ~ 15

20 Barrero-Gil A, Alonso G, Sanz-Andres A. Energy harvesting from transverse galloping. *Journal of Sound and Vibration*, 2010, 329(14):2873 ~ 2883

21 Mehmood A, Abdelkefi A, Hajj M R, et al. Piezoelectric energy harvesting from vortex-induced vibrations of circular cylinder. *Journal of Sound and Vibration*, 2013, 332(19):4656 ~ 4667

22 Abdelkefi A, Najar F, Nayfeh A H, et al. An energy harvester using piezoelectric cantilever beams undergoing coupled bending-torsion vibrations. *Smart Materials and Structures*, 2011, 20(11):115007

23 Wang J L, Zhou S X, Zhang Z E, et al. High-performance piezoelectric wind energy harvester with Y-shaped attachments. *Energy Conversion and Management*, 2018, 181:645 ~ 652

24 曹东兴,孙培峰,姚明辉,等. 双稳态屈曲梁压电发电结构非线性动力学分析. 动力学与控制报,2016,14(6): 520 ~ 525(Cao D X, Sun P F, Yao M H, et al. Nonlinear dynamics of bistable buckled beam piezoelectric harvesters. *Journal of Dynamics and Control*, 2016, 14(6): 520 ~ 525(in Chinese))

25 郭抗抗,曹树谦. 压电发电悬臂梁的非线性动力学建模及响应分析. 动力学与控制学报, 2014, 12(1): 18 ~ 23(Guo K K, Cao S Q. Nonlinear modeling and analysis of piezoelectric cantilever energy harvester. *Journal of Dynamics and Control*, 2014, 12(1): 18 ~ 23(in Chinese))

26 Chen W, Zhang Q, Wei W, et al. A low-frequency, wideband quad-stable energy harvester using combined nonlinearity and frequency up-conversion by cantilever-

surface contact. *Mechanical Systems and Signal Processing*, 2018, 112:305 ~ 318

27 唐炜,王小璞,曹景军. 非线性磁式压电振动能量采集系统建模与分析. 物理学报,2014,63(24):76 ~ 89 (Tang W, Wang X P, Cao J J. Modeling and analysis of piezoelectric vibration energy harvesting system using permanent magnetics. *Acta Physica Sinica*, 2014,63(24):76 ~ 89(in Chinese))

28 Ding L, Zhang L, Bernitsas M M, et al. Numerical simulation and experimental validation for energy harvesting of single-cylinder VIVACE converter with passive turbulence control. *Renewable Energy*, 2016, 85:1246 ~ 1259

29 章大海,王文颢,李天娇,等. 非对称粗糙带对单圆柱流致振动特性影响研究. 船舶力学, 2019, 23 (10): 1177 ~ 1186(Zhang D H, Wang W H, Li T J, et al. Research on fluid-induced vibration of single circular cylinder with asymmetrical roughness strip. *Journal of Ship Mechanics*,2019,23(10):1177 ~ 1186(in Chinese))

30 Wang J L, Zhao G F, Zhang M, et al. Efficient study of a coarse structure number on the bluff body during the harvesting of wind energy. *Energy Sources Part A Recovery Utilization and Environmental Effects*, 2018, 40(13-18): 1788 ~ 1797

31 Zhu H J, Gao Y, Zhou T M. Flow-induced vibration of a locally rough cylinder with two symmetrical strips attached on its surface: Effect of the location and shape of strips. *Applied Ocean Research*, 2018, 72:122 ~ 140

32 Wang J L, Zhao W, Su Z, et al. Enhancing vortex-induced vibrations of a cylinder with rod attachments for hydrokinetic power generation. *Mechanical Systems and Signal Processing*, 2020, 145:106912

33 Kang S, Ryu S, Song S. Quantification of VIV-driven energy transfer for a circular cylinder with a pair of bumps at Reynolds number 150. *Journal of Mechanical Science and Technology*, 2020, 34(3):1139 ~ 1147

34 Gang H, Tse K T, Wei M H, et al. Experimental investigation on the efficiency of circular cylinder-based wind energy harvester with different rod-shaped attachments. *Applied Energy*, 2018, 226(SEP. 15):682 ~ 689

35 Jie S, Gang H, Tse K T, et al. Performance of a circular cylinder piezoelectric wind energy harvester fitted with a splitter plate. *Applied Physics Letters*, 2017, 111(22): 223903

36 Wang J L, Gu S H, Abdelkefi A, et al. Enhancing piezoelectric energy harvesting from the flow-induced vibration of a circular cylinder using dual splitters. *Smart Materials and Structures*, 2021,30(5):05LT01

37 Noel J, Yadav R, Li G, et al. Improving the performance of galloping micro-power generators by passively manipulating the trailing edge. *Applied Physics Letters*, 2018, 112(8):083503

38 Ding L, Yang L, Yang Z M, et al. Performance improvement of aeroelastic energy harvesters with two symmetrical fin-shaped rods. *Journal of Wind Engineering and Industrial Aerodynamics*, 2019, 196(109):104051

39 Wang J L, Sun S K, Tang L H, et al. On the use of metasurface for Vortex-Induced vibration suppression or energy harvesting. *Energy Conversion and Management*, 2021, 235:113991

40 周帅,张志田,陈政清,等. 大长细比钝体构件涡激共振与驰振的耦合研究. 工程力学,2012,29(1):176 ~ 186 (Zhou S, Zhang Z T, Chen Z Q, et al. Research on coupling of the vortex-excited resonance and galloping of the bluff body with large slenderness ratio. *Engineering Mechanics*,2012,29(1):176 ~ 186(in Chinese))

41 Yang X K, He X F, Li J J, et al. Modeling and verification of piezoelectric wind energy harvesters enhanced by interaction between vortex-induced vibration and galloping. *Smart Materials and Structures*, 2019, 28(11): 115027 (13pp)

42 Yang K, Su K W, Wang J L, et al. Piezoelectric wind energy harvesting subjected to the conjunction of vortex-induced vibration and galloping: comprehensive parametric study and optimization. *Smart Materials and Structures*, 2020,29(7): 075035

43 He X F, Yang X K, Jiang S L. Enhancement of wind energy harvesting by interaction between vortex-induced vibration and galloping. *Applied Physics Letters*, 2018, 112(3):033901

44 Qin W Y, Deng W Z, Pan J N, et al. Harvesting wind energy with bi-stable snap-through excited by vortex-induced vibration and galloping. *Energy*, 2019, 189(PT. 1):116237.1 ~ 21

45 Wang J L, Zhang C Y, Gu S H, et al. Enhancement of low-speed piezoelectric wind energy harvesting by bluff body shapes: Spindle-like and butterfly-like cross-sections. *Aerospace Science and Technology*, 2020:105898

46 Sun W, Jo S, Seok J. Development of the optimal bluff body for wind energy harvesting using the synergetic effect of coupled vortex induced vibration and galloping phe-

nomena. *International Journal of Mechanical Sciences*, 2019,156: 435 ~445

47 Wang J L, Gu S H, Zhang C Y, et al. Hybrid wind energy scavenging by coupling vortex-induced vibrations and galloping. *Energy Conversion and Management*, 2020, 213: 112835

48 Yang K, Qiu T, Wang J L, et al. Magnet-induced monostable nonlinearity for improving the VIV-galloping-coupled wind energy harvesting using combined cross-sectioned bluff body. *Smart Materials and Structures*, 2020, 29(7):07LT01 (7pp)

49 Arrieta A F, Neild S A, Wagg D J. Nonlinear dynamic response and modeling of a bi-stable composite plate for applications to adaptive structures. *Nonlinear Dynamics*, 2009, 58(1):259 ~272

50 Mcinnes C R, Gorman D G, Cartmell M P. Enhanced vibrational energy harvesting using nonlinear stochastic resonance. *Journal of Sound and Vibration*, 2008, 318(4-5):655 ~662

51 Huang D M, Zhou S X, Yang Z C. Resonance mechanism of nonlinear vibrational multistable energy harvesters under narrow-band stochastic parametric excitations. *Complexity*, 2019, 2019

52 Kim P, Seok J. Dynamic and energetic characteristics of a tri-stable magnetopiezoelastic energy harvester-ScienceDirect. *Mechanism and Machine Theory*, 2015, 94:41 ~63

53 Bibo A, Alhadidi A H, Daqaq M F. Exploiting a nonlinear restoring force to improve the performance of flow energy harvesters. *Journal of Applied Physics*, 2015, 117 (4): 045103

54 Stanton S C, Mcgehee C C, Mann B P. Reversible hysteresis for broadband magnetopiezoelastic energy harvesting. *Applied Physics Letters*, 2009, 95(17):421

55 Erturk A, Inman D J. Broadband piezoelectric power generation on high-energy orbits of the bistable Duffing oscillator with electromechanical coupling. *Journal of Sound and Vibration*,2011, 330(10):2339 ~2353

56 Li H T, Qin W Y, Lan C B, et al. Dynamics and coherence resonance of tri-stable energy harvesting system. *Smart Materials and Structures*, 2016, 25(1):015001

57 Naseer R, Dai H L, Abdelkefi A, et al. Piezomagnetoelastic energy harvesting from vortex-induced vibrations using monostable characteristics. *Applied Energy*, 2017, 203(oct.1):142 ~153

58 Alhadidi A H, Daqaq M F. A broadband bi-stable flow energy harvester based on the wake-galloping phenomenon. *Applied Physics Letters*, 2016, 109(3):033904

59 Zhang L B, Abdelkefi A, Dai H L, et al. Design and experimental analysis of broadband energy harvesting from vortex-induced vibrations. *Journal of Sound and Vibration*, 2017, 408:210 ~219

60 Yang K, Wang J L, Yurchenko D. A double-beam piezo-magneto-elastic wind energy harvester for improving the galloping-based energy harvesting. *Applied Physics Letters*, 2019, 115(19):193901

61 Wang J L, Geng L F, Yang K, et al. Dynamics of the double-beam piezo-magneto-elastic nonlinear wind energy harvester exhibiting galloping-based vibration. *Nonlinear Dynamics*, 2020, 100(12):1963 ~1983

62 胡晨阳,吴子英,常宇琛,等.改进的双稳态涡激振动能量收集器的发电性能研究.机械科学与技术,2020,39(10):1555 ~1562(Hu C Y, Wu Z Y, Chang Y C, et al. Study on power generation performance of improved bistable vortex-induced vibration energy harvesting. *Mechanical Science and Technology for Aerospace Engineering*,2020,39(10):1555 ~15623(in Chinese))

63 Zhou S X, Cao J Y, Inman D, et al. Broadband tristable energy harvester: Modeling and experiment verification. *Applied Energy*, 2014, 133:33 ~39

64 Zhou S X, Cao J Y, Lin J, et al. Exploitation of a tristable nonlinear oscillator for improving broadband vibration energy harvesting. *European Physical Journal-Applied Physics*, 2014, 67(3):30902

65 Zhou S, Li J, Wang J, et al. Vortex-induced vibrational tristable energy harvester: Design and experiments. IOP Conference Series Materials Science and Engineering, 2019, 531:012011

66 谭红波,刘丽兰,薛白鸽.三稳态驰振能量捕获器发电性能研究.机械科学与技术,2020,39(10):1539 ~1546(Tan H B, Liu L L, Xue B G. Exploring power generation performance of tristable galloping vibration energy harvest er. *Mechanical Science and Technology for Aerospace Engineerin*, 2020, 39(10): 1539 ~ 1546(in Chinese))

67 Wang J L, Geng L F, Zhou S X, et al. Design, modeling and experiments of broadband tristable galloping piezoelectric energy harvester. *Acta Mechanica Sinica*, 2020,36(3): 592 ~605

68 Yang Y W, Tang L H, Equivalent circuit modeling of piezoelectric energy harvesters. *Journal of Intelligent Materi-*

al Systems and Structures, 2009. 20(18):2223 ~ 2235

69 Tang, L H, Zhao L Y, Yang Y W, et al. Equivalent circuit representation and analysis of galloping-based wind energy harvesting. *IEEE/ASME transactions on mechatronics*, 2015, 20(2):834 ~ 844

70 Zhao L Y, Yang Y W. Comparison of four electrical interfacing circuits in wind energy harvesting. *Sensors and Actuators A Physical*, 2017,261:117 ~ 129

71 Zhao L Y, Tang L H, Member, et al. Synergy of wind energy harvesting and synchronized switch harvesting interface circuit. *IEEE/ASME Transactions on Mechatronics*,2016,22(2): 1093 ~ 1103

72 王定标,苏震,史兆臣,等. 基于等效电路法的变三角截面驰振压电能量收集研究. 固体力学学报,2019,40(5):441 ~ 450(Wang D B, Su Z, Shi Z C, et al. Research on piezoelectric energy harvesting of variable triangular cross-sections based on equivalent circuit method. *Chinese Journal of Solid Mechanics*, 2019,40(5):441 ~ 450(in Chinese))

73 靳遵龙,李国平,王军雷,等. 被动湍流控制圆柱驰振能量收集的等效电路研究. 振动与冲击,2020,39(9):207 ~ 213(Jin Z L, Li G P, Geng L F, et al. Equivalent circuit analysis of the galloping-based piezoelectric energy harvester with a passive turbulence control cylinder. *Journal of Vibration and Shock*,2020,39(9):207 ~ 213(in Chinese))

74 Wang J L, Tang L H, Zhao L Y, et al. Equivalent circuit representation of a vortex-induced vibration-based energy harvester using a semi-empirical lumped parameter approach. *International Journal of Energy Research*, 2020, 44(6):4516 ~ 4528

75 Lan C B, Tang L H, Harne R L. Comparative methods to assess harmonic response of nonlinear piezoelectric energy harvesters interfaced with AC and DC circuits. *Journal of Sound and Vibration*, 2018, 421:61 ~ 78

76 Zhang C Y, Hu G, Yurchenko D, et al. Machine learning based prediction of piezoelectric energy harvesting from wake galloping. *Mechanical Systems and Signal Processing*, 2021, 160(8):107876

RESEARCH PROGRESS OF PIEZOELECTRIC ENERGY HARVESTING FROM FLOW-INDUCED VIBRATION *

Sheng Lijie　Wang Junlei†

(*College of Mechanical and Power engineering, Zhengzhou University, Zhengzhou* 450001, *China*)

Abstract Flow-induced vibration is a typical phenomenon of fluid-structure interaction. The periodic force caused by flow-induced vibration will cause fatigue damage to the structure, which leads to safety problems. In recent years, with the development of vibration energy harvesting technology and the application of low energy consumption products such as microelectronics, wireless networks and Micro electro mechanical system. The energy capture technology based on flow-induced vibration has attracted more and more researchers' attention, but at the same time there are many problems in the research of flow-induced vibration technology. The current development status of current flow-induced vibration energy capture technology is reviewed, and several measures to improve the efficiency of flow-induced vibration energy capture devices are discussed. Finally, the current problems and challenges in the field of flow-induced vibration energy harvesting are summarized, and the prospects for the future development of flow-induced vibration energy harvesting are put forward.

Key words flow-induced vibration, vortex-induced vibration, galloping, energy harvesting technology

---

Received 15 July 2021, revised 12 August 2021.

* The project supported by the National Natural Science Foundation of China (51977196)

† Corresponding author E-mail: jlwang@zzu.edu.cn