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Editorial

Energy harvesting: materials, structures and methods

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Abstract With the advent of technology miniaturization, portable electronic devices are evolving at a rapid pace, especially in the field of wireless sensor networks for IoT applications. On the contrary, battery technology has not seen a similar growth in miniaturization. Also, frequent replacement of batteries is challenging for devices located in remote places. Energy harvesting from ambient conditions may be one solution to the above challenges. The IoT and powering of portable devices are becoming increasingly popular among researchers working on structural health monitoring systems. Thermoelectric, piezoelectric, electromagnetic, electrostatic and triboelectric mechanisms are the major energy transduction methods adopted in the development of energy harvesting devices. Many of these devices have limitations including relatively low power density, narrow bandwidth and low efficiency at lower frequencies. The virtual International Conference on Advances in Energy Harvesting Technology (ICAEHT 2021, 18–20 March 2021) was organized to bring together researchers working on energy harvesting to discuss possible solutions to the above limitations and future directions. The content of this special issue was inspired from the contributions and discussions made during the ICAEHT 2021 and a few more from invited papers. The 19 selected papers cover thermoelectric, piezoelectric, electromagnetic and triboelectric energy harvesters. Modelling, analysis, optimization, control, experimentation, energy management and application aspects of the harvesters are covered in this special issue entitled "Energy harvesting: materials, structures and methods". We hope that readers will find this special issue quite interesting, encouraging and novel.

1 Preliminary comments

Energy harvesting from ambient environments is becoming increasingly popular among designers and researchers working on structural health monitoring systems and charging of portable devices. Non-linear structures, multifunctional materials, multi-field transducers and power electronics should be engaged to develop and meet efficiency demands and overcome bandwidth issues and size/mass limitations directed towards practical applications.

We wish to thank everyone who supported this special issue, right from the reviewers to the journal support team and the editors of EPJST. The authors deserve special thanks for their enthusiastic response and hard work in support of our idea. The special issue was open to technical reviews and contributory papers alike. We hope that this volume will contribute constructively to discussions on non-linear effects in energy harvesting, structural health monitoring and control, metamaterial/metastructures for energy harvesting, multifunctional materials for energy harvesting, thermoelectric energy harvesting, ocean energy harvesting and energy harvesting circuits.

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2 Contributed papers in this special issue

This special issue is a collection of 19 selected contributions covering a range of interesting problems related to the modelling, analysis, experimentation and control of energy harvesting systems.

The special issue begins with a review article on vibration energy harvesting. Prajwal et al. [1] present a review of recent developments in the field of vibration energy harvesting including modelling, analysis and techniques involved in converting available vibration energy into electrical energy. The authors highlight the latest trends in electronic converters used for energy harvesting.

A dynamic magnifier based on a four-bar mechanism for amplifying the output power from a harvester is proposed by Suresh et al. [2]. The authors consider piezoelectric harvester beams of two different geometries. The first harvester beam consists of a copper substructure beam, and the other is fabricated by attaching two extended aluminum beams to the existing copper substructure beam at the tip end. A significant enhancement of the output voltage from the proposed harvester is observed.

Mei et al. [3] present a theoretical, numerical and experimental work on a beam-type rotational piezoelectric energy harvester (PEH). The authors propose a mathematical model considering the installation angle. In order to study the effect of centrifugal force, the rotational radius is established in a rotational coordinate system. Theoretical analyses are conducted to investigate the influence of the parameters on the dynamic performance of the PEH. The work demonstrates the significant influence of the installation angle on the related power generation in the effective frequency range.

Vasconcellos et al. [4] explore the performance of a metastructure with non-linear absorbers for vibration attenuation and energy harvesting. The metastructure considered involves two main concepts: conservation of total mass and strain energy. These are achieved by keeping the metastructure mass constant with or without the absorber and using the same strain energy for both the non-linear and linear absorbers. The authors use modal analysis of the base structure and the metastructure with linear and non-linear absorbers in their assessment of the performance. The results show that the displacement amplitude response is insensitive to the non-linearity far from the tuned frequency. The energy localization is lower at the last absorber and spreads along the structure when non-linear absorbers are used. The total power harvested by the metastructure is increased considerably near the first resonance. Chaurha et al. [5] also present a study on a metastructure considering the effect of functional gradation. A parametric study is performed to tune multicell models to enhance vibration suppression along with energy harvesting performance. Functional gradation in an eight-cell model is attained from softening to hardening using an exponential and power law to explore the dual functionality. The softening effect reduces the resonant peak, and the phononic metastructure exhibits absolute band gaps for certain configurations.

de Moura et al. [6] analyse a smart beam coupled with piezoelectric materials connected to resonant shunt circuits to study the dynamic behaviour in unimorph and bimorph configurations. The authors use a spectral element method (SEM)-based approach for the periodic smart structure. This method is capable of efficiently analysing the various configurations of periodicity and piezoelectric attachments. The frequency response function (FRF) amplitudes are attenuated around the tuning frequencies, demonstrating the effects of the smart beams connected with shunt circuits. Locally resonant behaviour is observed at the same attenuation frequencies, indicating a direct effect of the resonating circuits and vibration attenuation. The study explores the potential of the SEM approach for the analysis and design of more complex configurations of smart structures in an efficient framework.

Kecik and Mitura [7] present a numerical and experimental analysis of a two-degrees-of-freedom (DoF) electromagnetic energy harvester with variable friction. The authors consider the oscillation of a levitating permanent magnet in a tube with a coil wrapped around it. A comparison study with different friction coefficients is presented. The friction significantly affects the power output and dynamics of the harvester. Friction can reduce the multi-stability and power recovery efficiency.

The dynamics of a magneto-elastic oscillator with symmetric and asymmetric bistable potential wells are investigated by Giri et al. [8]. The authors develop an autonomous algorithm which categorizes the response obtained into seven unique primary attractor solutions subjected to different harmonic excitations and initial conditions. The numerical modelling-based investigation confirms that small and moderate levels of asymmetry have no significant influence on the cross-well periodic solution. Also, chaos-prone solutions can be restrained with these asymmetry levels. This results in efficient energy harvesting and enhanced life expectancy of the harvester.

Hollm et al. [9] investigate the dynamics of a wave energy converter based on a guided inclined point absorber. The authors present simulations and experiments to study the effect of different inclination angles of the guided point absorber on motion amplitudes and velocities in regular and irregular waves for energy harvesting applications. A random non-white Gaussian stochastic process based on a sea spectrum is used to represent irregular waves. The inclination angle is found to have a significant influence on the energy harvesting output. The authors also extend the study to a simple control strategy to further enhance energy harvesting output.

Arandel et al. [10] present the design and simulation of an electromagnetic rolling mass wave energy harvester for oceanic drifter applications. This harvester consists of a rolling mass resonator with oscillating permanent magnets in a coil system. The rolling mass frequency is tuned to match the drifters to achieve resonance. The authors use OrcaFlex to obtain the motion vectors of the drifter and MSC ADAMS to obtain harvester results. An output of 23 mJ is harvested during a 1-min simulation.

Ribeiro et al. [11] explore chaos control to stabilize system dynamics and recover a regular voltage signal which is suitable for use in the applications of interest. The authors employ an extended delayed feedback method that combines a displacement actuator and a digital controller to implement the control mechanism. A mathematically formulated control strategy is tested on a bistable energy harvesting system frequently operating in a chaotic regime. The controller exhibits the ability to stabilize the chaotic dynamics at a very low energetic cost.

Muralidharan and Ali [12] investigate the potential of an array of mechanically coupled bistable piezoelectric cantilevers for broadband harvesting under harmonic excitation. The non-linear dynamics and harvesting performance of the harvester array are studied numerically. Parameters including tip mass, coupling springs and cart masses are considered to study the effect on the coupled system response and energy harvesting performance. The authors exploit the complex dynamics of coupled bistable systems for broadband energy harvesting.

The assessment parameters of a fractional-order capacitor of a piezo-patch harvester located on a multicopter are presented by Koszewnik [13]. The electroelastic fractional-order model of the piezo composite in modal coordinates is analysed. Simulations are carried out to determine a proper location for the piezo harvester on the multicopter and to assess its electrical parameters. The experiments carried out indicate that the harvested power can be used to power up small devices on a multicopter.

Naifar et al. [14] present a design study of a non-linear electromagnetic converter using a magnetic spring. A model is developed to describe the force acting on a moving magnet based on the volume and geometry of fixed magnets. A parametric study is conducted to tune the non-linearity and coil axial position. The harvester resonant frequency is tuned based on the results from the analytical model.

Ševeček et al. [15] analyse a piezoelectric skin on a vibrating structure for energy harvesting and structural health monitoring applications. The relation between the layout of polyvinylidene fluoride (PVDF) patches and electrical power generated at different vibration conditions is assessed using computational and experimental analysis. The effective distribution of patches and optimal resistance in the circuit for maximum power harvesting are obtained by numerical analyses. The numerical calculations are supported by experimental results, making this modelling approach suitable for the design of effective piezoelectric skins on (large) vibrating structures for both energy harvesting and structural health monitoring applications.

Investigations of the stability and effectiveness of wing-based piezoaeroelastic systems with combined non-linearities are performed by Bouma et al. [16]. A mathematical model with structural and aerodynamic non-linearities such as stall effects of the energy harvesting system is derived. The study is carried out in the presence of freeplay and structural non-linearities for multiple solutions, which affect the overall effectiveness of the system. The results show that energy harvesting at speeds lower than linear speed is possible in the presence of freeplay. The quadratic structural non-linearity is found to decrease as the gap size of the freeplay increases. It is also shown that the stall effect plays an important role for the case when the angle of attack is greater than 2°, as it affects the Hopf bifurcations in the pitch degrees of freedom.

Margielewicz et al. [17] present a study on the efficiency of a quasi-zero stiffness system and determine the effect of its stiffness and geometry on the potential barrier. The numerical study shows that the potential barrier width is limited by an increase in the equivalent stiffness of the quasi-zero stiffness system. However, the barrier width increases with the spacing between the compensating springs. The authors compare the results of the quasi-zero stiffness system with a triple-well system and determine the effect of excitation frequency and amplitude on the energy harvesting efficiency.

Alvis et al. [18] investigate the simultaneous control and energy harvesting from the system. The absorber amplitude is restricted by stoppers to improve the energy harvested and broadband frequency. The asymmetry in the stoppers' gap and finesses are optimized in order to generate optimal energy. Medium stiffness is shown to have a significant impact on both the dynamics of the primary system and the level of power harvested by the absorber. A solo stopper configuration with a gap distance of 0.02 m improves the peak power by 29% and average power by 9% over the symmetric case. With an asymmetric stiffness configuration with one stiffness of 1×10^5 N/m and the other 5×10^3 N/m, a gap size of 0.02 m shows an improvement of 25% and 8% in the peak and average harvested power, respectively. Hard stopper configurations show improvements with asymmetric cases, but do not outperform the system without amplitude stoppers.

Kondaguli and Malaji [19] present modelling and numerical simulation of various shapes of thermoelectric generators (TEGs) to evaluate their efficiency. The legs of different shapes of the TEG are evaluated with constant isothermal boundary conditions. The authors consider variation in the cross section of the leg, leg length, hot-side and cold-side junction temperature and thermal stress to study the effect on the energy harvested. The results show that trapezoid generators are better from an efficiency point of view, whereas legs with a square or circular cross section produce more power.

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