論 文 の 内 容 の 要 旨

論文題目　Enhancement of energy harvesting from nonlinearly vibrating systems under harmonic and random excitations
（調和およびランダム励振による非線形振動系からのエナジーハーベスティングの性能向上）

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Different energy sources exist in the environment, in which the vibration sources can be found everywhere in daily life, and hence the concept of electrical energy harvesting from ambient vibration sources has been of popular interest of research in recent years. Due to recent advancements in microelectromechanical systems, the power consumption of electrics had been dramatically decreased. It becomes a considerable application to use small-scale low powered wireless sensors in inaccessible or hostile environments. On the other hand, the vibrations in many situations can be very large; for example, the vibrations of vehicle systems, can be 100 W or more. Up to new, linear resonant energy harvesters had been one of the most common type of energy harvesters with the limited response bandwidth. Many efforts were made to overcome this problem, covering resonance frequency tuning techniques, multimodal energy harvesting, frequency up-conversion, and so on. However, those well-known methods are still restricted in the field of linear energy harvesting, which already studied by many researchers.

The energy harvesting by application of self-excited vibration also attracted some attentions; however, its applicable area for energy harvesting is generally limited to a certain field. For example, the energy harvester subjected to a uniform and steady flow. Another apparent issue is that the performance of the energy harvester is significantly limited by the fundamental frequency of the device. One typical case is the beam-type wind energy harvester using the theory of Karman Vortex Street.

As a result of those problems, a large body of work has been, and still is being, devoted to investigating the energy harvesting performance by introducing dynamic nonlinearities into devices - this forms the main focus of this thesis. Therefore, the present work in this thesis is to enhance the energy harvesting efficiency applying nonlinearly vibrating systems, which can be divided into two parts based on the excitation types: harmonic and random excitations.

For the case of the harmonic excitation, it is mainly focused on the monostable energy harvester with Duffing-type nonlinearity. It is validated that at relatively high excitation levels, both low- and high-energy solutions can coexist for the same combinations of parameters, and the existence of the high-energy orbit can achieve higher energy harvesting effectiveness with wider bandwidth applications. It is certainly favourable to maintain the high-energy orbit for boosting the response and a larger output power. However, if the operating point falls down to the low-energy orbit, the wider bandwidth compared with the linear energy harvester will be impaired. The frequency or amplitude sweeps of the excitation is usually used in order to reach a desirable high-energy orbit and investigate the influence of the nonlinearity by many researchers. This gives a limitation on practical implementation, because the external vibration source cannot be arbitrarily controlled.

Another approach is to add disturbance or initial conditions for the energy harvesters, but no physically feasible mechanism has been fabricated and tested. To solve this problem, a stiffness tunable nonlinear vibrational energy harvester is proposed, whose nonlinearity emerges from the interaction forces with two neighbouring permanent magnets facing with opposing poles. The hypothesis is that the jump from the low-energy orbit to the high-energy orbit can be triggered by tuning the stiffness of the system, without changing the frequency or the amplitude of the excitation. Theoretical investigations show a methodology for tuning stiffness, and experimental tests also validated that the proposed method can be used to trigger a jump to the desirable state, and also tune the resonant frequency when the external ambient vibration varies; thereby, this can broaden the bandwidth of the energy harvester. Considering the tuning procedure of the stiffness, it means the additional energy consumption, though it does not require the constant energy supply. Another improved approach is further investigated to stabilise the high-energy orbit. The equivalent linear stiffness of the energy harvester can be varied by tuning the damping level of the device. Same as the stiffness tunable nonlinear energy harvester, from this adjustment the variation of the equivalent stiffness generates a corresponding shift in the frequency-amplitude response curve, which can trigger a jump and stabilise the high-energy orbit. The approach has been observed to require little additional energy supply for the adjustment and stabilisation, because it needs less energy for tuning the damping than the direct stiffness tuning by mechanical method.

Having stabilised on the high-energy orbit, it is necessary to further optimise the system for maximum power output. However, there has been much recent interest in the response analysis of the monostable nonlinear energy harvesters and comparison with their linear counterpart, but few literatures about the optimisation of the nonlinear energy harvester. Same as the linear energy harvester, the Duffing monostable energy harvester can also be optimised to maximise the available electrical power. With the consideration of the unconstrained and constrained electrical damping and stroke of the energy harvester, the analytical optimisation and numerical studies are demonstrated under the different conditions with the designed harvesting devices. The optimisation works can comprehensively provide the design rules of the monostable nonlinear energy harvester under harmonic excitations.

Furthermore, this thesis also focuses on the nonlinear energy harvesting techniques to random excited energy harvesting scenarios, because the vibration sources in the environment usually present time-varying properties, even completely random.

It is firstly concentrated on the influence of the stiffness nonlinearity on the transduction of the energy harvester, and the relative performance of linear, monostable hardening-type and bistable energy harvesters are comparatively investigated with the careful consideration of the constrained electrical damping and stroke of the device. General conclusions are drawn based on the numerical and experimental observations, which provide the guidance for the design of the randomly excited energy harvesting devices.

In spite of the comparative performance study of different kinds of energy harvesters, it is the passive energy harvesting approach by using several kinds of existing typical configurations. Then, motivated by how to actively enhance energy harvesting efficiency from random excitations, another novel approach is proposed and improved based on the theory of stochastic resonance. Stochastic resonance is a physical phenomenon through which the throughput of energy within an oscillator excited by a stochastic source can be boosted by adding a small modulating excitation. The hypothesis is that such stochastic resonance can be efficiently realised in a bistable mechanism, and the feasibility of implementing stochastic resonance is investigated for energy harvesting. Experimental results confirm that the addition of a small-scale force to the bistable system, excited by a random signal apparently, leads to a corresponding amplification of the response. Thereby, the proposed approach is a promising way to improve the energy harvesting performance under certain forms of random excitations.