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学位授与の日付	2017 年 9 月 25 日	
論　　文　　名	「Development of nonlinear piezoelectric vibrational energy harvester for human motion （人体運動を利用する非線形圧電振動発電素子の開発）」	
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論文要旨

In recent years, vibrational energy harvesters (VEHs) have attracted onsiderable attention since it is believed that it could be a promising alternative source to power microelectronics by converting ambient vibrations into electricity. Big attention has been paid to piezoelectric VEHs (pVEHs) because of its simple energy conversion mechanism. pVEHs with linear-resonant suffer from a drawback of narrow bandwidth. For the practical applications, various strategies for broadening the operating bandwidth of pVEHs have been addressed. Nonlinear energy harvesting, which is based on nonlinear resonance concept, is one of the strategies. Typically, there are two methods to introduce nonlinearity within the vibrating structure, which are magnetic coupling and inherent structural nonlinearity. The nonlinearity can be categorized into monostable, bistable and tristable oscillators. The degree of stability depends on the wells allowed in the oscillator. The monostable oscillator is divided into softening and hardening based on the restoring force of oscillator. This study focused on the theoretical analysis of linear-resonant and monostable nonlinear pVEHs, and on the development of bistable pVEH for human motion.

This thesis is divided into two parts; the first part focuses on the comparison between the linear and monostable nonlinear pVEHs for human motion based on the theoretical simulation using analytical harmonic balance and numerical methods. The role of nonlinear stiffness in the performance of pVEHs was discussed. The electromechanical responses of pVEHs were analyzed based on Duffing oscillator at a deterministic harmonic excitation of fundamental vibration characteristics (2 Hz, 1 $m{\cdot}s^{-2}$), which corresponds to human walking. From the analytical calculation, it was found that strong nonlinearity is difficult to achieve for the softening case because of the small potential well.

Therefore, the response of linear and hardening nonlinear pVEHs to a combined vibration, which consists of a fundamental deterministic vibration and a second vibration, was analyzed numerically. The fundamental vibration has a frequency of 2 Hz and an acceleration of 1 $m \cdot s^{-2}$ and the additional second has an acceleration of 0.5 $m \cdot s^{-2}$and a frequency varied from 1.5 to 2.5 Hz. The numerical calculation showed that the linear-resonant pVEH has much output power than the hardening pVEH. This is reasonable because for a nonlinear system the linear superposition is not obtained principally. Despite the general believe of the benefits of the nonlinear VEHs compared to the linear VEHs, the numerical results obtained within this part indicate that nonlinearity does not have a significant advantage on the energy harvesting from human walking, which consists of a fundamental vibration with additional small vibration. Therefore, the bistable pVEH was developed for the human motion.

Three methods are reported to induce the bistability states within vibrating beam-structure, which are the use of buckled beams, the nonlinear magnetic coupling, and the inverted pendulum of beam. However, the integration of magnets and piezoelectric parts, and the low robust structure limit applications. Bistable states can be created by applied an axially compressive force, of magnitude larger than first critical buckling load, on the beam. In addition, the buckling states of beam-structure can be induced during the fabrication process. This brings easy fabrication of micro-and macro-scale devices using the buckled beams.

The conventional bistable pVEHs based on pre-buckling beams with 3 hinged-hinged and clamped-clamped end conditions suffer from the high triggering force required for snapping process. The second part of thesis presented a pVEH based on an axially constraint buckled beam to solve this issue. For the developed structure, the energy harvesting functionality can be enhanced via nonlinear interwell vibrations triggered at low frequencies and small amplitudes. A prototype of the pVEH was fabricated and investigated experimentally. The second part of thesis divided into two portions.

In the first portion, the electromechanical responses of the nonlinear bistable pVEH for slow hand shaking vibrations with a frequency of 1-2 Hz were investigated. Form the static characterizations, the direct correlation between the strain and displacement was experimentally observed. This correlation was used to interchange the phase portraits of velocity and displacement with voltage–strain diagrams, rather than voltage-input acceleration diagrams as a measure of the snap through action of bistable buckled beam structure. The attached mass to the beam played an important role in minimizing the acceleration needed to snap through action. The minimum input acceleration for the snapping transition was 11.6 m/s^2 at the attached mass of 14.6 g. A maximum generated power was 11.3 μW at a buckling height of 0.5 mm and the mass 26 g. The proper buckling states and the associated attached mass for human motion were discussed.

In the second portion, the contributions of interwell and intrawell motions to the power output were discussed. It was observed that the presence of the sub-resonance frequencies, due to the inrawell motions, has a significant contribution to the power generated at the deeper buckling states. The results indicate that the low-frequency motional energy is up-converted to higher frequencies on the proposed axially constraint bistable system. The proposed structure leads to not only operation at low operating frequency, 1.3-3.2 Hz but also with peak amplitudes of 11.3-33.7 m/s^2. 4

This thesis focused on the application of nonlinear pVEHs for human motion. It was found that linear-resonant pVEH generates high energy than the nonlinear counterpart for human motion with low frequencies 1.5-2 Hz. The bistable pVEH based on axially constraint buckled-beam was exploited to harvest the electrical power from the human motion. Moreover, the experimental results indicate the up-conversion of a low-frequency motional energy to higher electrical frequencies for the applied vibrations.

審査結果の要旨

近年、環境中に存在する熱や振動などの微小エネルギーから電力を得るエナジーハーベスティング技術が注目されている。様々な研究が行われている一方で、最も期待が大きい人体の運動から発電については、小型、軽量、利便性を兼ね備えた方法の開発が望まれている。人体の運動は非調和な振動であるため、発電素子には広い周波数帯域を有することが必要であることから、非線形共振現象の利用が期待されている。
本論文は、人体運動を対象とした振動発電素子における非線形共振現象の利用の効果を明らかにすることを目的として研究を行ったものであり、以下の成果を得ている。

（1）ソフトニング型およびハードニング型の非線形共振特性を有する圧電振動発電素子を人体運動に適用した場合に得られる効果について、理論的に解析した。解析には調和バランス法および数値解析法を用いた。ソフトニング型では、低周波かつ大振幅の人体運動においてはポテンシャル障壁による閉じ込めが不十分で安定解が得られないことを明らかにした。ハードニング型ではそのような問題が生じないが、単純な線形共

振特性を有する振動発電素子に対して、優位な発電量の増大が期待できないことも明らかになった。以上の結果から、ソフトニング型およびハードニング型の非線形共振現象は、人体運動からの発電において有用性はないと結論付けた。

（２）上記とは異なる非線形共振現象であるバイステーブル型の有用性について、実験的検証を行った。従来のバイステーブル型発電素子は、大きな加速度の印加が必要、破損しやすい等の課題を有していたことから、それを解決できる新規な構造を考案した。開発した素子を用いて、人体運動下における発電特性を解析した。その結果、従来の報告に比べて小さな加速度の印加で、バイステーブル型に特有のスナップスロー応答を得ることに成功した。

（３）開発した素子に印加する振動の条件を変化させ、その応答を調べた。その結果、印加した振動が高周波の振動に変換されるアップコンバージョンと呼ばれる現象が発現することを見出した。発電特性を解析した結果、アップコンバージョン現象に起因した発電量が、全体の発電量の半分を占めていることを明らかにした。

以上の成果は、先行研究にいて提案されていたソフトニング型およびハードニング型の非線形共振現象には、振動発電素子の特性向上の効果が期待できないこと、一方でバイステーブル型では、アップコンバージョン現象の発現により発電特性が向上することを明らかにしたものである。また、申請者が自立して研究活動を行うのに必要な能力と学識を有することを証したものである。