論 文 の 内 容 の 要 旨

論文題目　Modeling and dynamic behavior analysis for energy harvesting systems in rotational motion considering effects of centrifugal force

（遠心力を考慮した回転運動中のエナジーハーベスティングシステムのモデル化と動的挙動解析）

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Many wireless sensors are widely used to realize the convenient life and intelligent industry via Internet of Things (IoT). The traditional method for power supply is the chemical batteries, whose disadvantages are the limited lifespan, maintenance difficulties and pollution issues. Recently, the energy harvesting from the ambient energies has been considered as a promising way to provide sustainable power supply for these wireless sensors. Lastly, a self-powered wireless sensor can be achieved for structural health monitoring. According to previous studies of the piezoelectric energy harvesters (PEHs) in rotational motion, few of them considered the effect of rotational motion, namely the centrifugal force was neglected in their theoretical models, leading to their dynamic mechanism being not completely revealed. In order to solve these issues, the author mainly focus on modeling and dynamic behavior analysis for energy harvesting systems in rotational motion considering effects of centrifugal force.

Firstly, a nonlinear PEH in rotational motion is proposed, and related theoretical model is derived in a rotational coordinate system based on Lagrange equation and energy method. It can be noticed that the rotational coefficients, including the angular displacement, angular velocity and angular acceleration, are coupled in the proposed theoretical model. It also can be found that when the effect of rotational motion is considered, the $K_c\dot{\theta}^2$ term related to the rotational speed is added. The experimental results of a symmetric tri-stable PEH confirmed that the K_c coefficient has a great effect on predicting the energy harvesting performance, especially for the high rotational speeds at which the centrifugal stiffening effect occurs.

In this dissertation, the nonlinearities of different PEHs are caused by the magnetically coupled configuration. The dipole-dipole method is adopted to calculate the nonlinear magnetic forces of two configurations. Most importantly, for the PEHs in rotational motion, the periodic gravity component of tip mass can be an exciting force for the piezoelectric beam vibration. Based on that, the energy harvesting performance of various PEHs, including bi-stable, symmetric tri-stable, asymmetric tri-stable and quad-stable configurations, are theoretically and experimentally investigated. The experimental results demonstrate that the nonlinearity can broaden the effective frequency range via reducing the potential barriers, especially for the quad-stable PEH. An interesting phenomenon is that when the rotational speed reaches a certain value (440 rpm), the centrifugal stiffening effect will appear, reducing the energy harvesting performance.

Next, according to the centrifugal stiffening effect, a passively self-tuning effect is achieved for energy harvesting enhancement. As observed from the proposed theoretical model, as the rotational speed increases, the corresponding axial tension due to the centrifugal force on the piezoelectric beam changes its resonance frequency. Thus, when the parameters of a PEH are in appropriate values, the resonance frequency is near or at the rotational speed in a wide frequency range. In the experiments, the bi-stable and tri-stable PEHs achieve the self-tuning effect in the ranges of 440 - 720 rpm and 990 - 1300 rpm, respectively, which are caused by the different rotational radiuses. Additionally, it is validated that a passively self-tuning method is effective way to widen the operation frequency bandwidth.

In order to further harvest low-frequency rotational energy (less than 120 rpm), an inverse PEH is installed in rotational motion, in which the centrifugal force is along with the inside of radial direction so that the centrifugal softening effect will be achieved. And the same nonlinear PEH is adopted for the experiments with forward and inverse configurations in rotational motion, which correspond to the centrifugal stiffening and softening effects respectively. The experimental results confirm that in low-frequency rotational motion, the inverse PEH is superior to the forward one, and the RMS voltage between 60 - 110 rpm can reach as high as 5 V, which is enough for powering a wireless sensor used for the structural health monitoring of the blade of a wind turbine.

This dissertation mainly focused on three keywords: rotational motion, centrifugal force and piezoelectric energy harvesting. All results demonstrate that the centrifugal force caused by the rotational motion has a great influence on the energy harvesting performance. Specifically, for the forward PEH, under high rotational speeds, the centrifugal force along with the outside of radial direction can lead to centrifugal stiffening effect, by which a passively self-tuning effect can be obtained to broaden the effective frequency range. For the inverse PEH, the centrifugal force along with the inside of radial direction can enhance the energy harvesting performance in low-frequency rotational motion via the centrifugal softening effect.