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Experimental and numerical investigations of the piezoelectric energy harvesting via friction-induced vibration

D.W. Wang[a], J.L. Mo[a,*], X.F. Wang[a], H. Ouyang[b], Z.R. Zhou[a,*]

[a] Tribology Research Institute, Southwest Jiaotong University, Chengdu 610031, China
[b] School of Engineering, University of Liverpool, Liverpool L69 3GH, UK

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ABSTRACT

In this work, piezoelectric energy harvesting via friction-induced vibration is investigated experimentally and numerically. A test setup which is able to generate friction-induced vibration and simultaneously harvest vibration energy is created. The experimental results verify the feasibility of energy harvesting via friction-induced vibration. They suggest that there is a critical driving speed for the friction system to generate strongest friction-induced vibration and output highest voltage; a larger normal load is beneficial for producing stronger vibration and outputting higher voltage; the external electric resistance has little effect on the vibration of the friction system, instead it will modify the output voltage amplitude within limits. To further understand the experimental findings, both the complex eigenvalue analysis and implicit dynamic analysis are performed in ABAQUS. The complex eigenvalue analysis further confirms the feasibility of energy harvesting by means of friction-induced vibration, and shows that the vibration in both tangential and normal directions can be harvested. The implicit dynamic analysis verifies the effect of driving speed and normal load on the system dynamics and harvested energy. Accordingly, a two-degree-of-freedom friction system model is proposed to qualitatively characterise the effect of external electric resistance on the system dynamics and harvested energy. This investigation offers quite a new way of harvesting vibration energy.

1. Introduction

With the fast development of wireless technology and micro-electromechanical systems (MEMS), low power portable electronics and wireless devices have been widely used in our daily life [1]. Considering that batteries used for charging these devices have a limited life, and the replacement or recharging of batteries is inconvenient, costly and sometimes impossible, developing self-powered technology by harvesting ambient energy has attracted more and more attention in recent years [2]. Among all the available ambient resources, ambient vibration energy is abundant and is easily accessible through MEMS technology, thus the conversion of vibration energy into electrical energy has been extensively investigated during the last twenty years [3–5].

Generally, there are five approaches to convert vibration to electric energy, i.e. electromagnetic, electrostatic, piezoelectric, magnetostrictive and triboelectric [5,6]. Among them, piezoelectric energy harvesting has become a growing interest as it has high power density and is not reliant on an external magnetic field or voltage source. Kim et al. [7], Erturk et al. [8] and Saadon et al. [9] all presented a comprehensive review of piezoelectric vibration energy harvesting technology. Moreover, various test setups (harvesters) [10–16], models (analytical models and finite element models) [17–25] and external circuits (SECE, SSHI) [26–30] have been established as well to investigate the conversion performance of ambient vibration energy to electric energy by using piezoelectric materials.

Nevertheless, a major challenge of vibration energy harvesting is that an energy harvester tends to convert energy most effectively only if the harvester is excited at its resonant frequency, which means that if the ambient vibration frequency shifts slightly from the resonant frequency of the harvester, the resulting energy output and conversion efficiency will dramatically reduce [31]. Hence, the harvester needs to be tuned to the dominant external frequency of the ambient vibration before its practical deployment. However, in the majority of practical situations, the ambient vibration is random and its frequency varies over a wide spectrum, thus broadening the effective frequency response bandwidth of harvesters is of significant for the design of vibration energy harvesters. Up to present, some solutions have been proposed to improve energy harvesting performance to some extent: Erturk et al. [32], Zhou et al. [33] and Wang et al. [34] exploited nonlinearity (of a

* Corresponding authors.
E-mail addresses: jlmo@swjtu.cn (J.L. Mo), zrzhou@home.swjtu.edu.cn (Z.R. Zhou).

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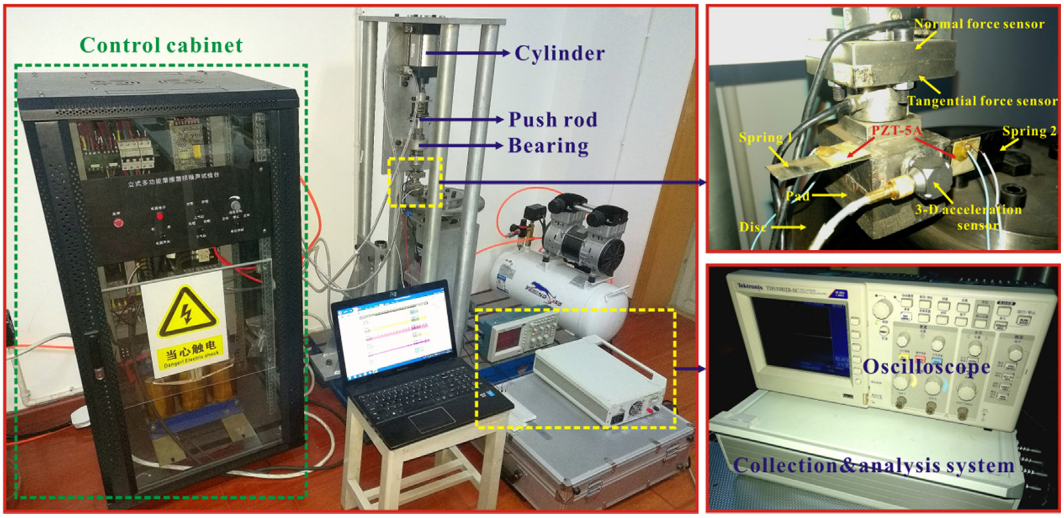

Fig. 1. Picture of the experimental test setup.

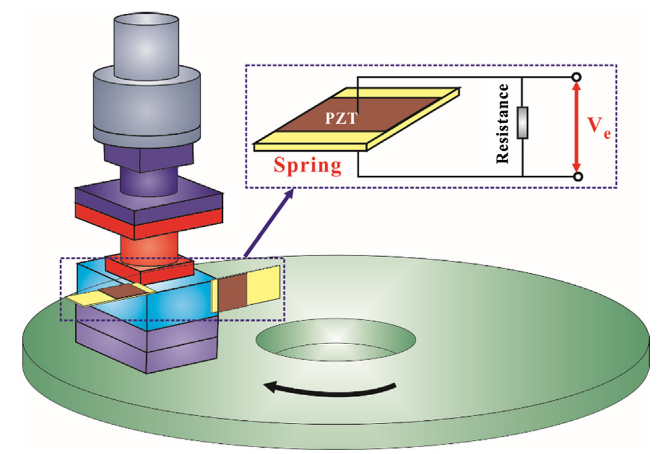

Fig. 2. Schematic diagram of the test setup and the corresponding harvesting circuit.

Table 1
The material parameters of the components of finite element model.

Parts	Density (kg/m^3)	Young's modulus (GPa)	Poisson's ratio
Top part	7670	196	0.3
Bearing	7800	172	0.3
Push rod	7670	196	0.3
Force sensor	7800	196	0.3
Support	7800	190	0.3
Pad back plate	7800	190	0.3
Friction material	4000	30	0.3
Disc	7800	220	0.3
Springs	7800	206	0.3

Table 2
The material parameters of the PZT-5A [56].

Engineering constants	E_1 = 60.61 GPa	ν_{12} = 0.512	G_{12} = 23.0 GPa
	E_2 = 48.31 GPa	ν_{13} = 0.289	G_{13} = 23.5 GPa
	E_3 = 60.61 GPa	ν_{23} = 0.408	G_{23} = 23.0 GPa
Piezoelectric coupling matrix	$\begin{bmatrix} 0 & 0 & 0 & 741 & 0 & 0 \\ -274 & 593 & -274 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 741 \end{bmatrix} 10^{-12}\text{m/V}$		
Dielectric matrix	$\begin{bmatrix} 1.505 & 0 & 0 \\ 0 & 1.301 & 0 \\ 0 & 0 & 1.505 \end{bmatrix} 10^{-8}\text{farad/m}$		

magnetic field) in enhancing vibration energy harvesting. Moure et al. [35], Yang et al. [13] and Zhou et al. [36] all proposed different structures of harvesters to improve energy harvesting performance. Stewart et al. [37], Kim et al. [38] and Du et al. [39] optimized the electrodes to improve power output. A more recently comprehensive review presented by Yang et al. [40] systematically summarized the

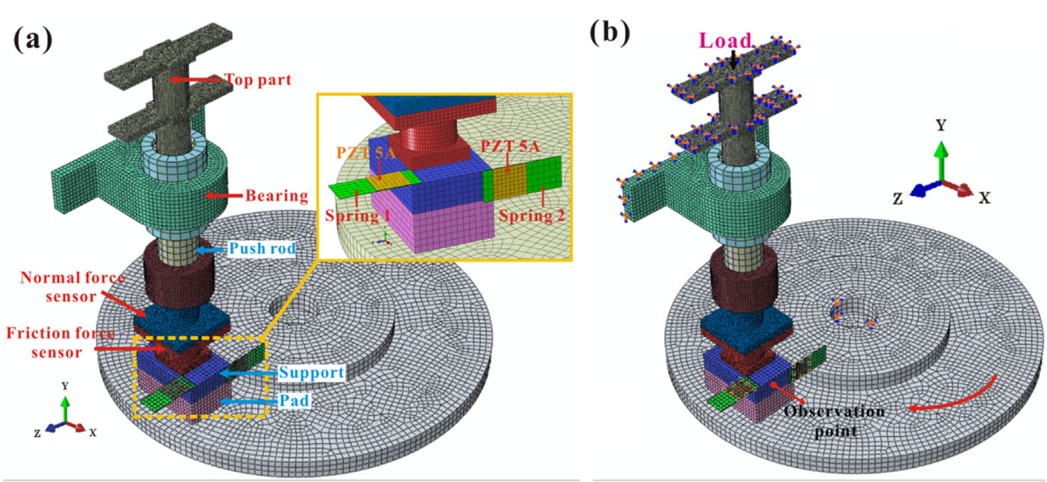

Fig. 3. The finite element model of the test system (a) and the constraint conditions of the finite element model (b).