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Shape optimization of railroad vibration energy harvester for structural robustness and power generation performance

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ABSTRACT

This paper presents design optimization of a stiffness component in a vibration energy harvester – diaphragm spring – for structural robustness and reliable power generation in railroad vehicle monitoring applications. Power generation is usually sufficient under the high impact loading of railroad operating conditions, but a highly durable harvester design has been a challenging issue. This paper performs a practical shape optimization of the diaphragm spring considering realistic vibrational loading conditions. In this study, we build the power spectrum density (PSD) of acceleration loading based on a railroad system design standard and use it for maximum stress estimation. A separate electromagnetic analysis has been conducted to determine the vibrational amplitude for the required power generation. A new conceptual diaphragm spring model has been chosen to minimize any unnecessary parasitic motion that could cause asymmetric spring deformation and excessive stress. The shape optimization on the new conceptual spring model has been conducted to obtain the new design that reduces the magnitude of stress concentration by 16% while satisfying the required vibration amplitude for energy harvesting.

1. Introduction

Recent technological advance has reduced the size and power consumption of wireless sensors and have opened new opportunities in structural health monitoring and real-time bio sensing. However, practical and durable power supply is still a challenge [1–4]. The requirements for an extended period of power supply and the disposal issues of chemical batteries have raised a clear need to use alternative energy sources. Energy harvesting can potentially increase the sensor's run-time by collecting wasted energy from its environment. Among various environmental energy sources, vibration energy has gained attention as a potential source to power these sensors due to its abundant availability, higher energy conversion efficiency, and environmental friendliness [5–7]. Vibration energy harvesters (VEH) have significant potential in a variety of applications, including bridges [8–10], pipelines [11], wind turbines, and railroad systems monitoring [12–14]. Particularly, for a wireless sensor deployed in inaccessible places, a self-powering sensor with VEH will enable diagnostic infrastructure with minimum or no maintenance [15–20].

A linear mass–spring–damper system has been one of the most common types of VEH due to its simplicity [21,22]. This system generates far more power when the excitation frequency matches the harvester's resonance frequency [23]. However, vibrating at resonance frequency introduces significant dynamic stress in a structure and can cause fatigue failure [24,25]. A successful VEH design needs to meet two performance requirements: power generation as well as structural robustness (durability). Even though plenty of research has reported power improvement, very little effort has been made to address the structural robustness issue since VEH research has been initiated. Furthermore, there have been few studies on reliable railroad harvester design in terms of structural robustness under harsh and random vibration environments. To this end, this paper presents a high-demand design optimization study of a railroad VEH to enhance structural robustness while satisfying power generation performance.

A bogie and axle system equipment is a framework underneath of the railroad vehicle which carry the wheels and experiences harsh vibration [26]. The harvester discussed in this paper supplies power to a wireless sensor module that monitors rail bogie axles and bearings [24]. Due to the limited space in the VEH discussed in this paper, we consider a flat, thin, compact spring – diaphragm spring. Circular diaphragm springs are widely used in industry, and the advantages of the Belleville and disk springs have been recently reported for an electromagnetic

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energy harvester [27,28]. However, little effort has been made to improve the diaphragm spring design [29,30]. From an engineering structural design point of view, to the best of the authors' knowledge, there has been no report on improving durability of diaphragm springs structural design under random excitation load. This paper will present a new multi-disciplinary design optimization strategy by implementing random vibration force data, recorded from railroad operation, to enhance the structural durability and energy harvesting performance of a railroad VEHs. The paper is organized as follows: Section 2 introduces the problems of the existing VEH design and presents the new conceptual design of the diaphragm spring; Section 3 discusses the design optimization formulation, optimization criteria, results, and the verification of results; and Section 4 concludes this paper. The Appendix addresses the coupled electro-mechanical analysis to estimate the required spring displacement, and the parameter study on the original diaphragm spring to motivate a new conceptual design and its shape optimization.

2. Optimization requirements for railroad VEH

The VEH discussed in this paper harvests vibration energy from the axles of a high-speed railroad vehicle (HEMU, new high-speed train under developing, max speed 430 km/h) during railroad operations. Fig. 1 shows a perspective view of the energy harvester studied in this paper [24]. The harvester is cylinder-shaped, approximately 80 mm-long, and has two circular diaphragm springs at both ends. These springs are dimensioned with outer diameter = 52 mm, thickness = 0.7 mm, and made of heat-treated SKD61 hot work tool steel

Table 1
Material properties of SKD61 [31].

Description	Symbol	Value
Density	ρ_s	7800 kg/m^3
Young's modulus	E_s	210 GPa
Poisson's ratio	ν_s	0.3
Yield strength	σ_{Ys}	1.52 GPa

(equivalent to AISI/ASTM BH13 steel, material properties in Table 1). They facilitate relative vibration between the center shaft and the moving cylinder, along the shaft direction. The coil bobbin is attached to the shaft and the magnets are mounted on the inside surface of the springs (not demonstrated in the figures). The shaft is connected to the end cap and outer housing (removed in the Fig. 1b to reveal the inside detail). When mounted on the railroad bogie (Fig. 1c), the shaft provides base excitation and causes relative vibrational motion between the shaft (coil bobbin) and the moving cylinder to induce current in the coil.

A FE model with fine mesh is chosen in this simulation (total elements = 60003; number of shell elements for spring = 20188). Fig. 2a and b show the FEM models of the whole VEH and the diaphragm spring, respectively. Two different kinds of element in ANSYS [32] are used in the FEM model: SHELL181 for the diaphragm springs and SOLID45 for the other components. Excitation load is applied along z direction, and translational (x, y) as well as rotational (rx, ry, rz) degrees of freedom are fixed at both ends of the shaft.

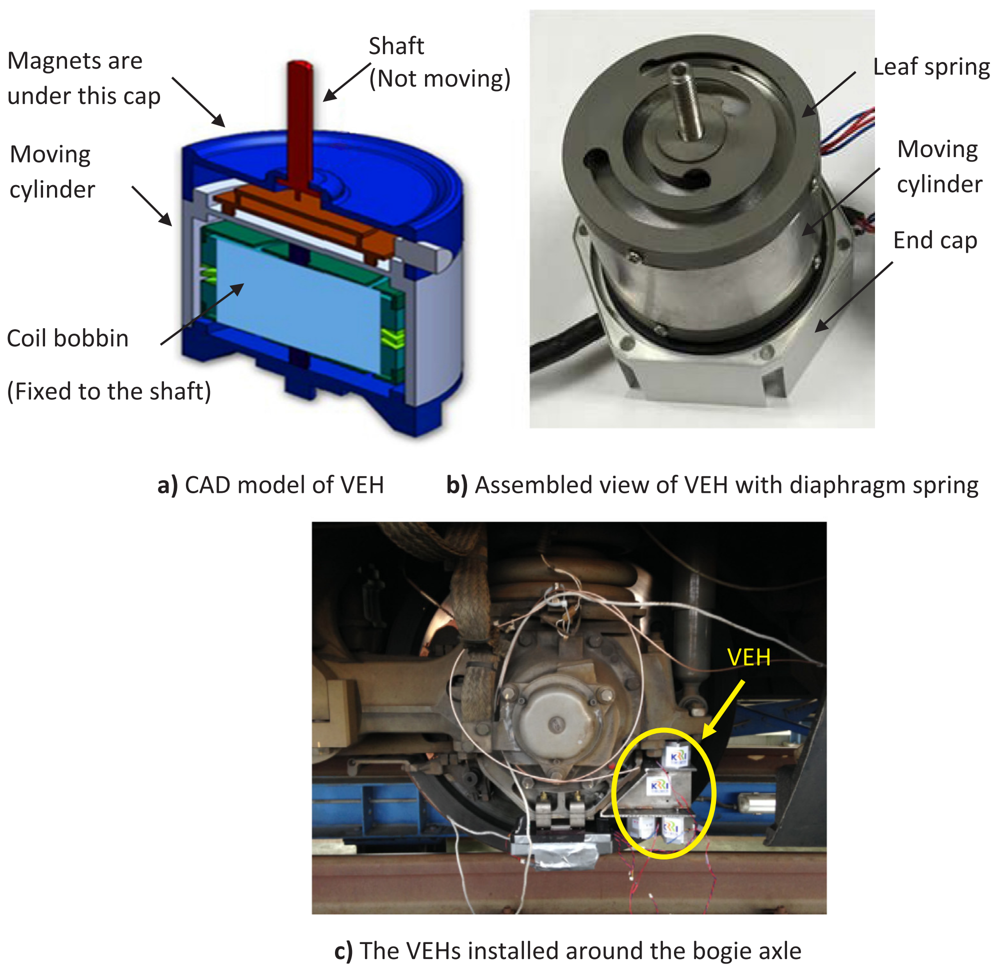

Fig. 1. Railroad vibration energy harvester model [24].