Sensors and Actuators A 244 (2016) 223–232

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Experimental investigation of performance reliability of macro fiber composite for piezoelectric energy harvesting applications

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A R T I C L E I N F O

Article history:
Received 10 February 2016
Received in revised form 15 April 2016
Accepted 15 April 2016
Available online 21 April 2016

Keywords:
Piezoelectricity
Energy harvesting
Macro fiber composite
Reliability
Fatigue strength
Fatigue
Durability

A B S T R A C T

Macro fiber composite (MFC) has been extensively used in actuator/sensor/harvester applications. Fatigue due to cyclic high electric fields in actuator applications has been studied extensively. However, fatigue failure of MFC due to high stress or strains in energy harvesting applications has attracted little attention. The aim of the study is to obtain the upper limit of dynamic strain on MFC which can be used as failure limit in the design process of piezoelectric energy harvesters (PEHs). The examined PEH is comprised of a cantilever beam made of aluminum and a patch of MFC bonded at its root for power generation. Energy harvesting tests are conducted at various base accelerations around 30 Hz (near resonant frequency) and the voltage output and maximum strain on MFC are measured. Severe loss in the performance of the harvester is observed within half million cycles of testing at high strain amplitude. Hence several reliability tests for extended periods of time are carried out at various strain amplitudes. The harvesters are tested at resonant frequencies around 30 Hz and 135 Hz for over 20 million and 60 million cycles, respectively. Degradation in voltage output, change in natural frequency and formation of cracks are considered as failures. Based on the experimental results, an upper limit of 600 $\mu\epsilon$ is proposed as the safe amplitude of strain for reliable performance of MFC. Tensile tests are also carried out on MFC patches to understand the formation of cracks and shift in resonant frequency at low strains. It is observed that cracks are formed in MFC at strains as low as 1000 $\mu\epsilon$. The observations from this work are also applicable to MFC bending actuators undergoing cyclic strains.

1. Introduction

Over the years, the emphasis on structural health monitoring using wireless sensor nodes (WSNs), intelligent control systems, sensing systems in smart buildings, low-power portable electronic devices, etc., has been increased. The systems in aforementioned applications are normally powered by chemical batteries that require periodic maintenance and proper disposal of hazardous chemical waste. With continuous reduction in power consumption of electronic circuitry, energy harvesting from ambient sources has emerged as an alternative solution for chemical batteries in low-power electronics and their applications. Vibration energy harvesting using piezoelectric transduction mechanism has received much attention due to its superior power density, ease of application, and scalability [1]. In the last decade, piezoelectric energy harvesting has been used in macro, meso, MEMS, and nanoscale applications as an alternative clean energy source [2]. A majority of research has focused on using piezoelectric energy harvesters (PEHs) as alternatives to chemical batteries for running low-power electronic devices and WSNs. The continuous reduction in size and power consumption of electronic devices and ongoing research in efficient power management of circuitry also help in practical implementation of PEHs for powering small scale devices.

Most of the designs of PEHs are linear energy harvesters that generate maximum power at the resonant frequency. Linear energy harvesters have been extensively studied using analytical models with experimental validation [3,4]. Finite element modeling has also been used for studying the dynamics of the linear harvesters [5,6]. The limitation of linear PEHs lies in their small half power bandwidth and hence they cannot produce usable power output away from resonant frequency. This issue poses serious challenge when the ambient vibrational energy is scattered over a range of frequency or for the case of random vibrations. Many techniques have been employed to broaden the bandwidth of the linear harvesters, including oscillator arrays, multi-modal oscillators, passive or active resonance tuning methods, and nonlinear techniques [7]. Despite of extensive work, researchers still face many challenges in practical implementation of PEHs. Even if the complete

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http://dx.doi.org/10.1016/j.sna.2016.04.043
0924-4247/

replacement of batteries by PEHs is not possible, the technology can be used for recharging batteries and for extending the lifetime of device.

Structural integrity and reliable performance over extended periods of time are important considerations in design and practical implementation of PEHs. In PEHs, brittle piezoelectric materials are very susceptible to fatigue failure due to the cyclic electromechanical loading on the harvester. Normally, a PEH is comprised of a piezoelectric material bonded to a substrate such as aluminum, brass, steel etc. Strength of some commercially available piezoelectric materials and commonly used substrate materials is given in Table 1. The values represent the strength of materials under various testing conditions such as quasi-static (tensile), fatigue (dynamic), bending, yielding, and fracture as notified in supplier's data sheet. The material strength is specified either in $\mu\epsilon$ (micro strain) or MPa (stress). The fatigue strength of the piezoelectric materials which is crucial information required for designing highly durable harvesters is not provided in most of the instances. From the tabulated data, it is conspicuous that the fatigue strength of piezoelectric materials is much less when compared to static and bending strength. Though macro fiber composite (MFC) has very high fracture strength, normally the material fails at much lower strain values under cyclic loading. Moreover, the information on the reliability of performance of materials such as number of cycles without any degradation is not available.

It is also evident from the table that the strength of the commonly used substrate materials is much superior to piezoelectric materials, indicating the possibility of early fatigue failure in piezoelectric materials. However, very few works have taken the material strength into consideration in the design of PEHs. Anton et al. [8] carried out 3-point bending tests on monolithic piezoceramics PZT-5A and PZT-5H, single crystal piezoelectric PMN-PZT, and commercially packaged QuickPack devices and reported their strengths to be used as the basis for the design of PEHs. These results are also included in Table 1 and it can be observed that they are among the highest as they are obtained from quasi-static bending tests. However, fatigue strengths are required for the design of harvesters rather than static strengths. Shafer and Garcia [9] derived an expression of the maximum tolerable input acceleration that a linear energy harvester can sustain based on the ultimate strength of the piezoelectric material and used this expression to determine the maximum harvested power corresponding to that acceleration. Upadrashta et al. [10] carried out a parametric study to obtain the optimal power output and bandwidth from a nonlinear harvester within allowable limits of strain on the piezoelectric material.

The fatigue behavior of piezoelectric materials has been extensively studied in the literature for actuator applications. Lupascu and Rödel [11] studied the microscopic mechanisms causing fatigue phenomenon in bulk PZT actuator materials under cyclic loading. The fatigue behavior of an adaptive structure comprising graphite/epoxy laminate with embedded PZT actuator was investigated by Mall and Hsu [12] for mechanical and electromechanical cyclic loading conditions. Only tensile stresses were applied in both cyclic loading conditions. Significant drop in actuator's voltage was observed within one million cycles and higher voltage drop was noticed as the mechanical stress was increased. A similar study was carried out by Yocum et al. [13] on a composite laminate with embedded piezoelectric actuator under fully reversed electromechanical cyclic loading. Chaplya et al. [14] studied the influence of electro-thermo-mechanical loading conditions on the actuation capabilities of five commercial piezoelectric stack actuators with emphasis on durability performance. Experimental results indicated a strong dependence of piezoelectric properties and power requirements on both mechanical loading and temperature. Wang et al. [15] evaluated the reliability of piezoelectric actuators under high cyclic electric fields with different magnitudes of mechanical preload. The results demonstrated a monotonic decrease in charge density and mechanical strain as loading cycles increased and the degradation was dependent on preload stress. Wang et al. [16] also studied piezoelectric and dielectric performance of a poled PZT subjected to electric cyclic loading conditions similar to high-field actuator applications. Bhattacharyya and Arockiarajan [17] investigated the influence of electrical fatigue on PZT for different loading frequencies and observed appreciable reduction in piezoelectric and dielectric coefficients for high number of cycles. In 2002, NASA Langley Research Center developed MFC which is a low-cost piezo composite actuator with high flexibility [18]. The MFC consists of a single layer of rectangular lead zirconium titanate (PZT) fibers embedded in epoxy matrix and kapton (polyimide) shell and offers high strain energy density, directional actuation, conformability, and durability. It was reported that the MFC is capable of enduring large strains about 2000 $\mu\epsilon$ (peak to peak) up to 100 million cycles without any degradation in free-strain performance. However, approximately 5% degradation in the performance was observed when the MFC was operated under cyclic loading of 1500 V (peak to peak), +300 V bias at 500 Hz. The MFC has also been used in special applications apart from typical actuators/sensors/harvesters. Tarazaga et al. [19] successfully tested the integration, packaging, deployment and thermal rigidization in vacuum, and operation of MFC in rigidizable inflatable boom application. The MFC was also used in health monitoring of the wing skin-to-spar joints of unmanned aerial vehicles [20].

As pointed out earlier, previous studies have evaluated the fatigue behavior of piezoelectric materials mainly for actuator applications. While strong electric fields are common in actuator applications, piezoelectric materials in PEHs experience high stress or strain fields. Furthermore, they undergo completely reversed cyclic loading, meaning equal amplitude of tensile and compressive strains with zero mean. Previous studies on actuators used either tensile strains or biased voltages which resulted in lower compressive strains. Though bulk piezoceramics exhibit good compressive strength [21], thin or film like patches used in actuators/sensors/harvesters do not have the capability to withstand high compressive loading. Moreover, high durability and structural integrity are required for piezoceramics for practical applications of PEHs. However, neither previous works nor supplier's data sheets provide estimates of material strength below which the piezoelectric materials perform with high reliability over extended periods of time.

In this work, the MFC is tested for reliability of its performance at different strain amplitudes with varied loading frequencies. Three types of experiments are performed for evaluating the performance of MFC. Firstly, energy harvesting tests are carried out with cantilever type PEH to estimate the voltage output and strain on MFC. The results prompted the authors to perform tensile tests on the MFC to understand certain phenomenon observed in the energy harvesting tests. Finally, several long duration tests are conducted with increased strain amplitudes at different frequencies to evaluate the reliability of harvester's performance. Based on the results, a safe dynamic strain limit on the MFC is proposed for reliable operation.

2. Energy harvesting tests

The schematic of PEH is shown in Fig. 1(a). The PEH is comprised of a cantilever beam made of aluminum (AL6061 T6) with a patch of MFC (M2807-P2) bonded to its root using DP-460 epoxy glue. A tip mass made of acrylic was attached to the free end of the cantilever beam to tune its resonant frequency. The tip mass has dimensions of 25 mm × 15 mm × 10 mm and a weight of 7.3 g. Strain gauge DSFLA-