Conference Proceedings of the Society for Experimental Mechanics Series

Alfred Wicks *Editor*

Shock & Vibration, Aircraft/Aerospace, and Energy Harvesting, Volume 9

Proceedings of the 33rd IMAC, A Conference and Exposition on Structural Dynamics, 2015

SEM

Springer

Alfred Wicks
Editor

Shock & Vibration, Aircraft/Aerospace, and Energy Harvesting, Volume 9

Proceedings of the 33rd IMAC, A Conference and Exposition on Structural Dynamics, 2015

Springer

Editors
Alfred Wicks
Department of Mechanical Engineering
Virginia Polytechnic Inst. & State Uni.
Blacksburg, VA, USA

ISSN 2191-5644 ISSN 2191-5652 (electronic)
Conference Proceedings of the Society for Experimental Mechanics Series
ISBN 978-3-319-15232-5 ISBN 978-3-319-15233-2 (eBook)
DOI 10.1007/978-3-319-15233-2

Library of Congress Control Number: 2015936333

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

Preface

Shock & Vibration, Aircraft/Aerospace, Energy Harvesting represents one of ten volumes of technical papers presented at the 33rd IMAC, A Conference and Exposition on Structural Dynamics, 2015, organized by the Society for Experimental Mechanics, and held in Orlando, Florida, February 2–5, 2015. The full proceedings also include volumes on Nonlinear Dynamics; Dynamics of Civil Structures; Model Validation and Uncertainty Quantification; Dynamics of Coupled Structures; Sensors and Instrumentation; Special Topics in Structural Dynamics; Structural Health Monitoring & Damage Detection; Experimental Techniques, Rotating Machinery & Acoustics; and Topics in Modal Analysis.

Each collection presents early findings from experimental and computational investigations on an important area within Structural Dynamics. Topics represent papers on practical issues improving energy harvesting measurements, shock calibration and shock environment synthesis and applications for aircraft/aerospace structures. Topics in this volume include:

Energy Harvesting
Adaptive Support
Shock Calibration
Operating Data Applications

The organizers would like to thank the authors, presenters, session organizers, and session chairs for their participation in this track.

Blacksburg, VA, USA — Randy Allemang

Contents

1 **From Preliminary Design to Prototyping and Validation of Energy Harvester for Shoes** 1
Elvio Bonisoli, Francesco Di Monaco, Nicolò Manca, Maurizio Repetto, and Stefano Tornincasa

2 **Issues in Experimental Testing of Piezoelectric Energy Harvesters** 11
Paulo S. Varoto

3 **Innovative Piezoelectric Cantilever Beam Shape for Improved Energy Harvesting** 19
Iman Mehdipour and Francesco Braghin

4 **Energy Harvesting from Piezoelectric Stacks Using Impacting Beam** 25
Yiğit Özpak, Murat Aykan, and Mehmet Çalışkan

5 **Nonlinear 2-DOFs Vibration Energy Harvester Based on Magnetic Levitation** 39
I. Abed, N. Kacem, M.L. Bouazizi, and N. Bouhaddi

6 **Parameter Identification of Riveted Joints Using Vibration Methods** 47
Elif Altuntop, Murat Aykan, and Melin Şahin

7 **Dynamic Ground Testing: Ground Vibration Tests Through Control Surface Excitation** 55
G. Osmond, A. Azzat, S. Leroy, and O. Delverdier

8 **Adaptive Support of an Aircraft Panel** 61
Manuel Baschke and Delf Sachau

9 **Calculating the Impact Force of Supersonic Hail Stones Using SWAT-TEEM** 67
Tyler F. Schoenherr

10 **Testing and Validation of the Dynamic Inertia Measurement Method** 81
Alexander W. Chin, Claudia Y. Herrera, Natalie D. Spivey, William A. Fladung, and David Cloutier

11 **Estimation of Amplitude-Dependent Resonance and Damping in MEMS Shock Accelerometers** 105
Jason R. Foley, Thomas J. Lagoski, Jontia Brown, and Jonathan Hong

12 **Development of a Mapping Function for a Low- to High-Amplitude Input** 115
Joshua H. Campbell, Janet C. Wolfson, Jacob C. Dodson, Alain L. Beliveau, Jonathan Hong, and Greg Falbo

13 **Experimental Study of Glass Fiber Reinforced Polyester Under Repeated Impacts** 129
Ahmed M. Elmahdy, Abdelhalim M. Elhabak, Mahmoud A. Adly, and Mohamed M. Elbawab

14 **FE Modeling of Paperboard Material Using Sandwich Structure Method** 137
W. Yang, M.W. Allin, and C.J. Dehenau

15 **Evaluation of Seismic Performance of an Excavation Support System** 141
Omer F. Usluogullari, Yalcin Bulut, and Ahmet Temugan

16 **Calculating Stress and Strain from Experimental ODS Data** 149
Brian Schwarz, Shawn Richardson, and Mark Richardson

17 Case Study: Modeling Generator Chassis Responses with ODS Data 161
Sze Kwan Cheah

18 Shock Calibration with Zero Shift Using a Digital Filter Technique 169
Hideaki Nozato, Wataru Kokuyama, and Akihiro Ota

19 Mechanical Shock Environment Synthesis for Structural Failure Elicitation 175
Cassidy L. Fisher, Kaitlyn S. Kliewer, Gregory M. Naranjo, Stuart G. Taylor, and Kendra Van Buren

20 Natural Frequencies of Layered Beams Using a Continuous Variation Model 187
Arnaldo J. Mazzei and Richard A. Scott

21 Analysis of H_∞ and H_2 Optimal Design Scheme for an Electromagnetic Damper with Shunt Resonant Circuit 201
Wai Kei Ao and Paul Reynolds

22 Orbit Stability Determination of Satellites Using Harmonic Force Excitation Analysis 213
Joshua Johnson, William H. Semke, Matthew Zimmer, and Ronald Fevig

23 Energy Harvesting Perspectives from Parametric Resonant Systems 223
Maryam Ghandchi Tehrani, Elvio Bonisoli, and Matteo Scapolan

Chapter 1
From Preliminary Design to Prototyping and Validation of Energy Harvester for Shoes

Elvio Bonisoli, Francesco Di Monaco, Nicolò Manca, Maurizio Repetto, and Stefano Tornincasa

Abstract Powering a remote wireless sensor is a challenging task if batteries are not suitable or enough capacious and their substitution is not feasible. In this project a remote wireless sensor is placed inside training shoes with the aim to collect and transmit data to evaluate and track the performance of an athlete. The primary energy source is the impact between the shoe and the ground while walking or running. The harvester has been designed by means of a multi-physics optimization based on an integrated electromagnetic-mechanical-electric-electronic simulator. Thus an automated optimization of the device with respect to volume constraints, magnets dimensions, induction coils placement and sizes and electric/electronic coupling have been performed to increase the average power extracted from the device at different speeds. These parameters are used as starting point for the product development phase in order to obtain a consistent number of prototypes and validate the simulations on these physical demonstrators. Finally, experimental outcomes evince the expected performance and a more than satisfactory agreement with the models, confirming the feasibility of the application.

Keywords Magneto-mechanical generator • Design and optimization • Shoe mounted device • Product development Experimental application

1.1 Introduction

Powering remote wireless sensors exploiting the energy of the environment with the aim of making their life independent from some energy limited power source like an electrochemical battery, is a challenging task. In addition, batteries are often not suitable or not enough capacious, their substitution is not feasible or simply annoying and they introduce some problems due to the toxicity of their chemicals.

Due to the growing of the wearable electronics market, one of the most debated topics in the field of energy harvesting is the power supply of all those devices where the energy source is the human body motion.

The present study proposes a wearable device totally powered by an Energy Harvester (EH): an electrically autonomous bluetooth step-counter placed in the sole of training shoes. This sensor allows collecting and transmitting data to a bluetooth receiver device, as a smartphone, to evaluate and tracking the athlete performance. Figure 1.1 schematically represents the working principle: at each step energy is harvested and used to power the electric interface.

Two possible strategies are available to collect energy in shoes during a step, usually by piezoelectric or electromagnetic transducers: sole deformation caused by the contact with the ground and shocks due to the impacts of the heel on the ground.

Piezoelectric devices using sole deformation are described by [1, 2] while inertial piezoelectric generators, composed by a cantilever beam with a mass on the free end, are described in [3, 4]. References [5, 6] present two linear electromagnetic generators with one or more magnets sliding into a guide placed horizontally in the shoe. These devices do not have any kind of springs. A rotary generator activated by a harm extending under the sole is described in [7]. A generator using a flow between two pumps placed in the front and in the rear of the sole is presented in [8].

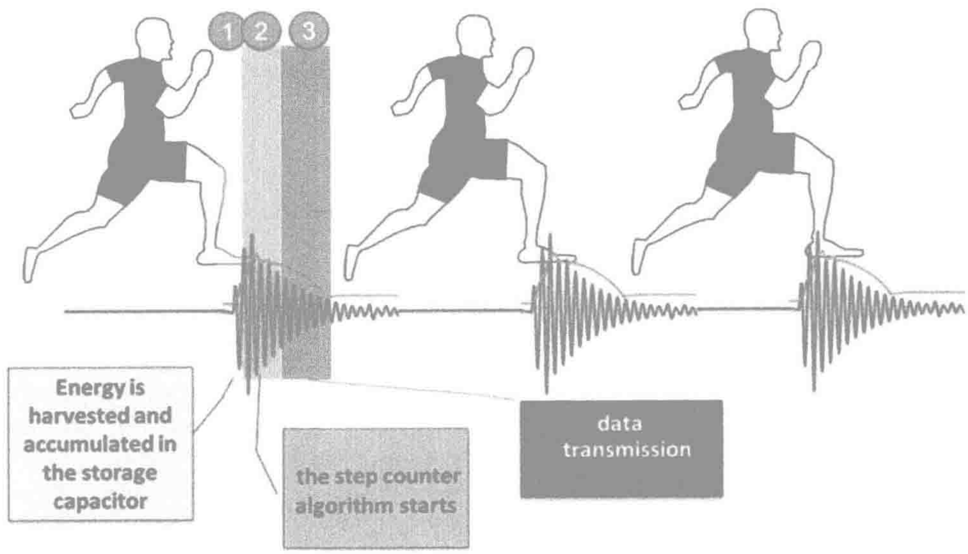
The proposed device is an electromagnetic energy harvester that exploits as primary energy source the impact of the heel on the ground during each step of walking or running activity. Differently from the devices presented in [5, 6] this one is placed in the heel with vertical sliding axis.

E. Bonisoli (✉) • F. Di Monaco • N. Manca • S. Tornincasa
Department of Management and Production Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
e-mail: elvio.bonisoli@polito.it

M. Repetto
Department of Energy, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

A. Wicks (ed.), *Shock & Vibration, Aircraft/Aerospace, and Energy Harvesting, Volume 9*,
Conference Proceedings of the Society for Experimental Mechanics Series, DOI 10.1007/978-3-319-15233-2_1

Fig. 1.1 Working principle



The harvester has been designed by means of a multi-physics optimization based on an integrated electromagnetic-mechanical-electric-electronic simulator. Thus, an automated optimization of the device with respect to volume constraints, magnet dimensions, induction coils placement and size and electric/electronic coupling have been performed to increase the average power extracted from the device at different walking speeds. These parameters represent the reference configuration for the product development phase in order to obtain a consistent number of semi-industrialized prototypes and validate the simulations on these physical demonstrators.

1.2 Device Description, Design and Optimization

The device consists of the main parts: the transducer for the vibrational energy harvesting and the conversion in electric energy, and the electric interface for step monitoring and data sending.

1.2.1 Harvester

The transducer is an electromagnetic linear generator. Its layout is shown in Fig. 1.2: a magnet can slide into a guide suspended between two springs and two coils are winded around the guide in opposite direction one each other. Inertial forces, due to the impact between the shoe housing the transducer and the ground during walking or running activity, induce motion in the magnet. The movement of the magnet causes a variation of the flux linkage in the coils and, consequently, a voltage is induced between the ends of the coils.

It is possible to represent the device as a single degree of freedom base-excited mass-spring-damper system where the transducer is considered as an inertial device, so that the forces act on its base and the mass vibrates freely. Two differential equations, one for the mechanical and one for the electrical domain, describe the system. In case of a generic electric load the two equations are:

$$\begin{cases} \frac{\mathrm{d}^2 z_\mathrm{r}}{\mathrm{d}t^2} = -\frac{\mathrm{d}^2 z_\mathrm{inp}}{\mathrm{d}t^2} - \frac{c}{m}\frac{\mathrm{d}\, z_\mathrm{r}}{\mathrm{d}t} - \frac{k}{m} z_\mathrm{r} + \frac{\lambda'}{m} i \\ \frac{\mathrm{d}\, i}{\mathrm{d}t} = -\frac{R}{L} i + \frac{V_L}{L} + \frac{\lambda'}{L}\frac{\mathrm{d}\, z_\mathrm{r}}{\mathrm{d}t} \end{cases} \tag{1.1}$$

where m is the mass of the moving magnet, k is the sum of the stiffness of the two springs, c is a generic dissipative viscous mechanical damping, z_{inp} is the base motion, z_r the relative position between magnet and base, λ' is the derivative of the magnetic flux linkage with respect to the relative displacement, R and L are respectively the resistance and inductance

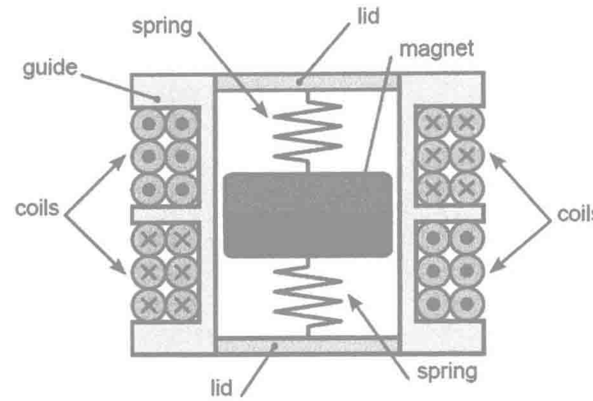


Fig. 1.2 Transducer layout

of the transducer coils, $V_L(i)$ is the voltage on the load, and i is the current [9, 10]. An accurate modelling of the system usually requires considering non-linearity of k and λ' that are function of the relative displacement [11, 12].

1.2.2 Electric Interface

The simplest electric load is a resistor directly connected to the ends of the coils of the transducer. This solution provides the maximum electrical power, but it does not allow energy storage; it follows that the EH can feed an electrical device only when the floating magnet of the transducer is moving. In order to store the recovered energy a capacitor is connected to the coils terminals and, as the provided current is alternating, a rectifier bridge is interposed between the capacitor and the transducer. Although this configuration represents the easiest way for storing, due to the voltage drops in the diodes of the rectifier, it implies very worst performance with respect to the previous case. Moreover, if the voltage between the ends of the rectifier is lower than the voltage of the capacitor, the transducer does not charge it.

To overcome the limits characterizing the bridge rectifier, an active electronic interface consisting in a step-up and a buck converter have been developed. The electronics interface is directly connected to the positive and negative terminal of the transducer. It consists of a full wave active boost converter with a transducer current control; this provides an optimum resistive load emulation independently from the signal provided by the transducer (shape and voltage level) and from the voltage stored on the output capacitor.

The interactions between the mechanical and electrical phenomena depend heavily on the power transferred by the seismic mass to the electrical load. In linear system response conditions, the optimal matching follows the well known maximum power transfer theorem. For instance, in [13] it has been demonstrated that the energy recovery in response to a sinusoidal vibration input whose frequency matches the resonant frequency of the mechanical system, is maximum in adapted load condition, namely when the resistive load R_L is:

$$R_L = R_{ADAPT} = R \tag{1.2}$$

However, due to the nonlinear effects present in the system, mainly the mechanical dissipative effects and the limited stroke of the floating magnet, the optimal resistor value is different from the one in (1.2) and it is typically larger. A theoretical analysis of this effect is present in [14], while here the best matching resistance value is calculated according to experimental evidences of the maximum power. Thus, the following equation is adopted through experimental evidence:

$$R_L = R_{OPT} = R_{ADAPT} + R_{ADD} \tag{1.3}$$

1.2.3 Application Constraints, Vibrational Input and Energy Requirements

The nature of the specific application imposes very stringent dimensional constraints to the device: a cylindrical shape volume of about Φ 27 × 16 mm that must contain the magneto-inductive energy harvester system for the power supply, the electronic interface for the data sending and the housing for the placing and the protection of the device itself in the sole of the shoe.

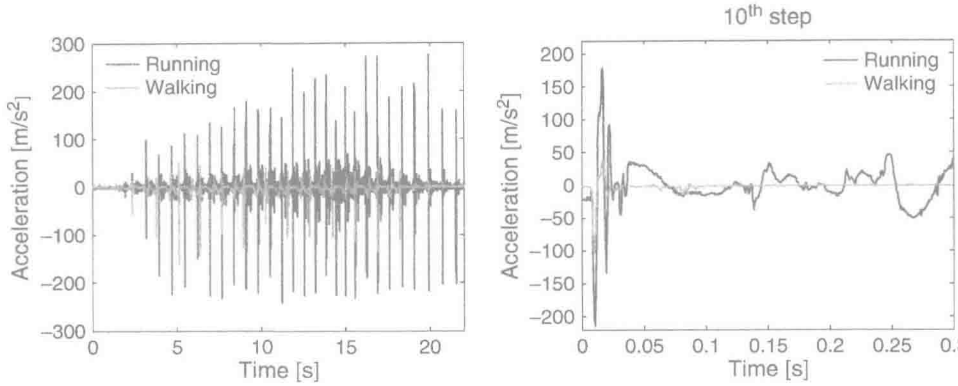


Fig. 1.3 Vertical acceleration experimentally measured in the heel during walking and running activity

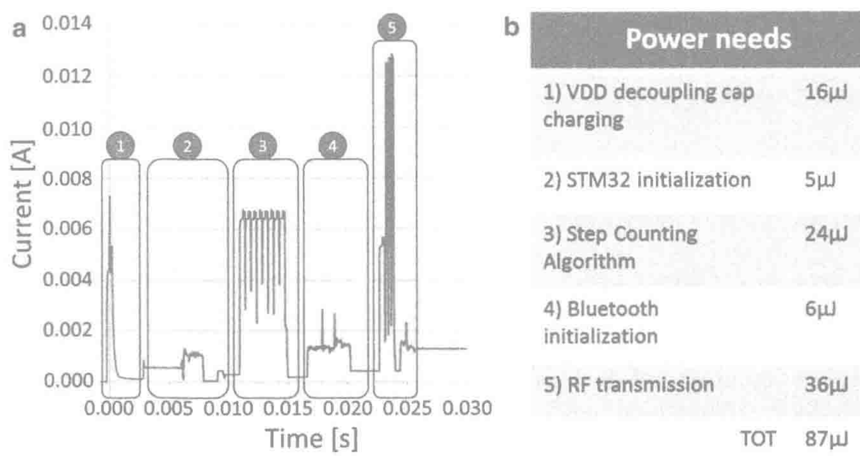


Fig. 1.4 Step counter system current absorption profile (**a**) and energy demand (**b**)

As Fig. 1.3 shows, the typical input acceleration profile for walking and running consists of a very limited in duration and amplitude excitation at each step comparable to a series of impulses.

Figure 1.4 represents the shape of the current consumption of the electric interface for the via bluetooth data transmission at each step, with the energy demand corresponding to each phase.

The total energy need of 87 μJ represents the minimum energy required for the transmission of the step. Considering the harvester interface and electric components efficiency, the energy that the transducer must provide for the step detection is 104 μJ.

1.2.4 Device Optimization

The stringent constraint imposed to the dimensions, the energy requirement of the electric interface for the step detection and the low intensity energy source imply a strict coupling between the mechanical and electrical characteristics upstream and downstream of the transducer with the objective of maximize the average power extracted from the device.

The implemented optimization algorithm exploits Pattern Search algorithm [15], a well know 0th order deterministic technique extensively used in the automated optimization environment.

Figure 1.5 summarizes the optimization loop steps based on an integrated electromagnetic-mechanical-electric-electronic simulator. This is a complete Matlab/Simulink model made to study the dynamic behavior of the device integrated in the optimization algorithm in order to maximize performance. Starting from the geometrical dimensions all the operative parameters (mass, springs, motion amplitude, dimensions of coils, number of turns in coils) are calculated. Through an automatic FEM model the flux linkage as a function of the magnet position is calculated. Then the system is simulated using a proper acceleration profile to excite the device. A full description of the simulation model is available in previous articles [16, 17]. Finally, the objective function implemented in the optimization algorithm is evaluated.

Figure 1.6 shows the evolution of the parameters and the objective function. A consistent improvement of the performance is found mainly due to the tuning of the elastic characteristic. Moreover the magnetic mass is increased by the extension of

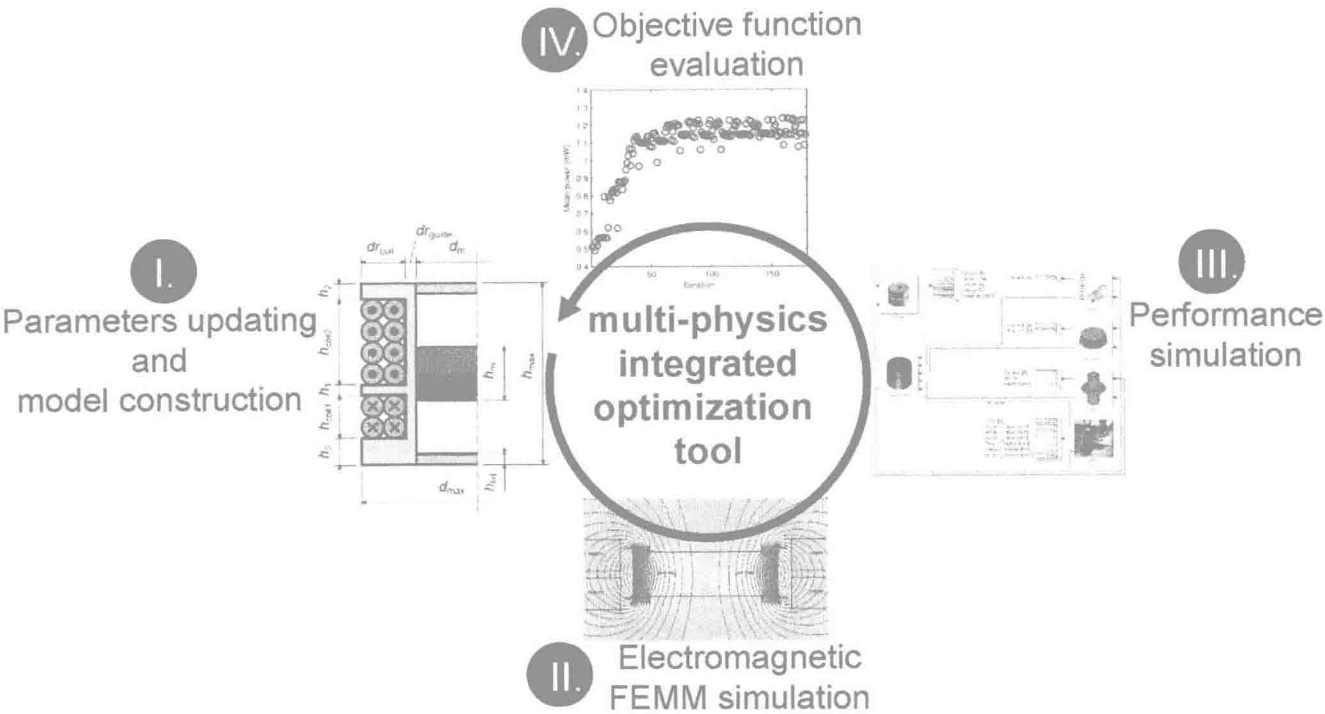


Fig. 1.5 Optimization loop

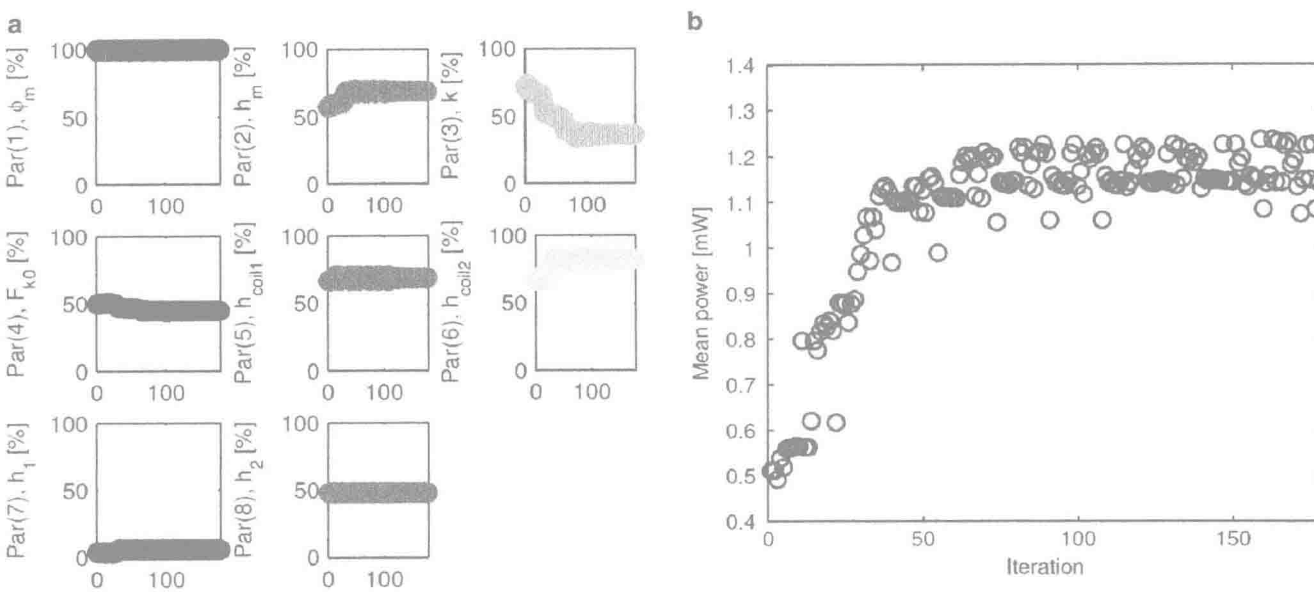


Fig. 1.6 Evolution of parameters (a) and objective function (b)

the magnet height, reducing the available stroke. The upper-coil length is also slightly increased. The simulation result emphasized the fact that initial device did not exploit all the available length of the stroke. The problem is fixed by softening its elastic characteristic and increasing the magnet height.

1.3 Product Development

The geometrical parameters resulting from the optimization process represent the reference configuration for the product development phase. The aim is to convert a virtual prototype in a real device ready for the medium-large scale production, fully functional and ready to use when placed in training shoes. In this context, a consistent number of prototypes have been made to experimentally validate the design process and prove the project feasibility.

1.3.1 Virtual Prototype

Starting from the reference configuration, a virtual prototype has been developed in according with the manufacturing requirements. The device consists of three plastic components, the case, the cap and the backcap, holding the cylindrical magnet and protecting the coils and the electronic interface. In order to optimize the available space, the elastic characteristic is obtained by means of two conic springs. As the step-counter will be insert in the sole of training shoes, a very important aspect is the design of the housing that must be sufficiently resistant to support the external load during the running and walking activity but, at the same time, not too thick in order to do not subtract space to the functional components. Therefore, 3D modelling, FEM analysis and the selection of the most suitable materials were key aspects in the product development of this device. The geometries that characterize the structural elements have been studied to minimize the internal stresses but always thinking to the ease of mounting. Figure 1.7 shows the section view of the device and an example of FEM analysis result.

Device behavior has been simulated in almost ideal condition neglecting friction. Figure 1.8 shows the simulated electrical performance in terms of average harvested power over 22 s of activity with the first step after 2.5 s, voltage trend and energy recovery with respect to the energy requirement of the tenth step. As it can be observed, the energy harvested during the step in this condition is fully sufficient to support the electric interface requirements.

1.3.2 3D Printed Prototypes

The first testing phase has been conducted on the 3D printed prototypes shown in Fig. 1.9. Tests have been performed reproducing on a shaker the same vibrational input used for the design process. Experimental evidences revealed that the springs, even if made of ductile iron, due to the strength of the magnetic induction of the floating element, shift on the lateral side of the magnet, precluded the right working of the device. To maintain the spring coaxial to the magnet, two plastic centering rings have been pasted on its flat surfaces. This allows the right linear oscillation of the floating elements but considerably reduces its available stroke resulting in a loss of performance of about 20 % when running as demonstrate by Fig. 1.10. Due to the smaller oscillation caused by the walking input, in this operative condition performance is the same as before; in fact, the stroke reduction do not affect magnet displacement when walking while strongly influence the behavior when running causing violent bumps that dissipate lot of energy.

Real performance is much lower than simulated in almost ideal condition due to friction between floating element and guide, materials efficiency, components production uncertainty, assembling imperfection and all the inconvenient that differs the real from the ideal world.

In order to overcome the loss due to the stroke reduction caused by the centering rings, ad hoc magnets, characterized by the same overall dimensions of the previous but presenting two centering holes on the flat surfaces, have been used. Exploiting larger stroke balances the smaller flux due to the smaller magnet volume. In addition, little adjustments of the guide component allowed reducing friction extending the magnet oscillation duration and increasing case resistance to the soldering high temperature.

1.3.3 Molded Prototypes

A consistent number of molded prototypes have been produced through a semi-industrialized manufacturing process, see Fig. 1.11. Plots in Fig. 1.12 demonstrate the convenience of adopting ad hoc magnets and the effectiveness of the adjustment performed on the main plastic component. No significant differences of the device performance is registered under walking

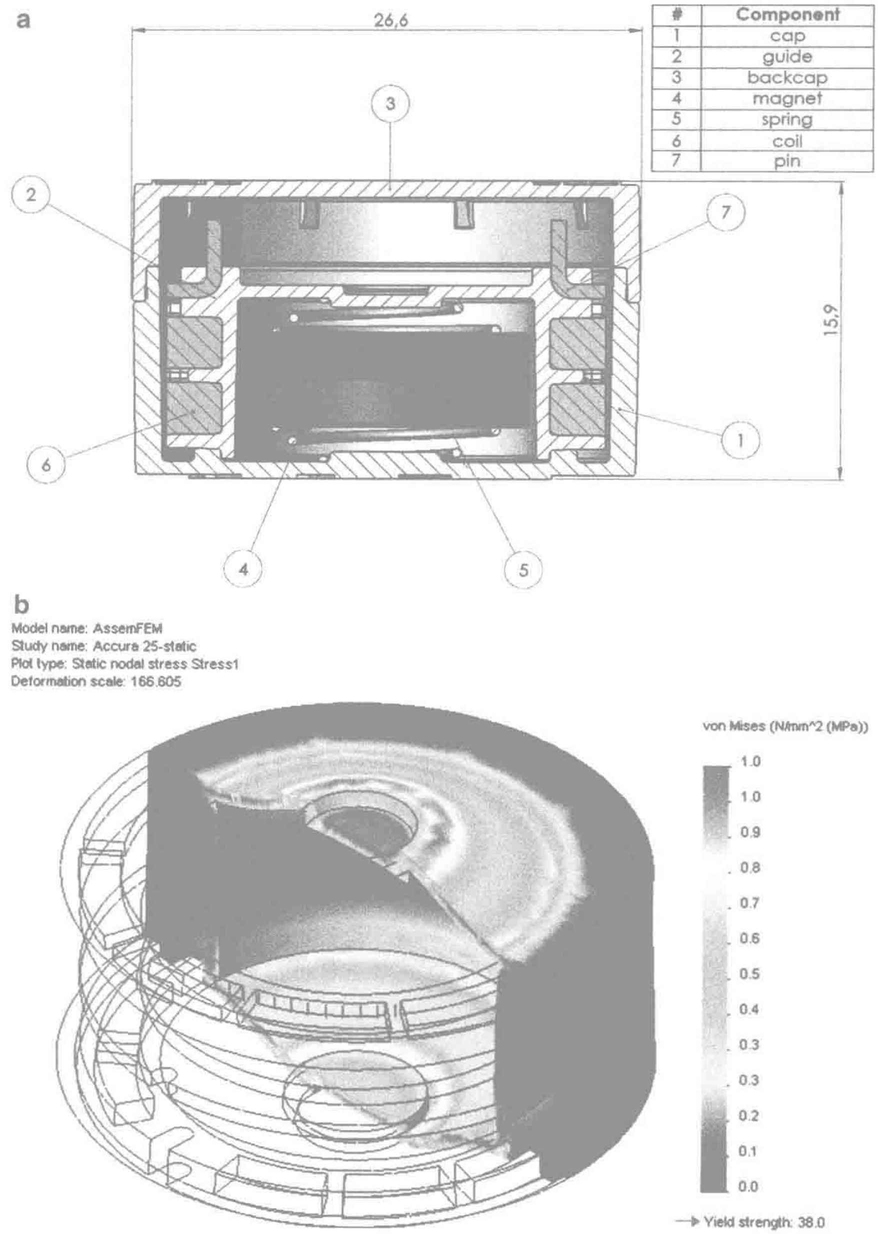


Fig. 1.7 Prototype layout (**a**) and example of FEM analysis result (**b**)

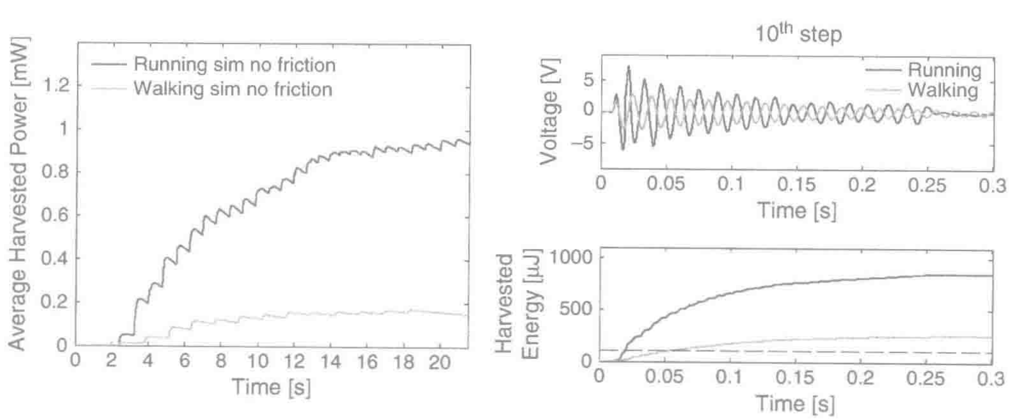


Fig. 1.8 Virtual prototype performance

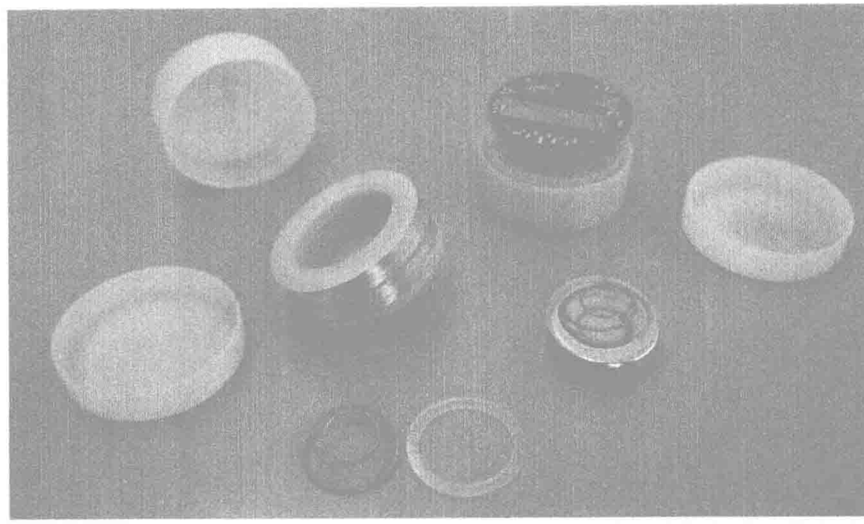


Fig. 1.9 3D printed prototypes

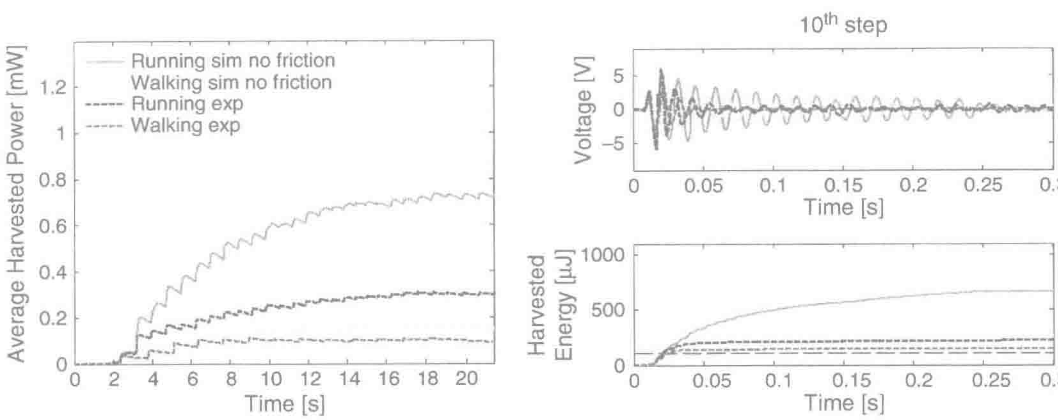


Fig. 1.10 3D printed prototypes performance

input, while, when running, a broad increase in the energy harvested is shown, both in simulation and in real test, about 40 %. The experimental recovered energy during a running step is about five times the required for the activity detection and data sending. Storing the energy surplus compensates the difference with respect to the requirements under very low intensity input allowing detecting every step during activity.

1.4 Conclusions

With the aim of feeding a bluetooth step-counter placed in the sole of a shoe for walking and running activity monitoring, a semi-industrialized set of EH prototypes with a dedicated electronic interface has been designed, produced and tested in order to demonstrate the feasibility of the project and validate the simulation model. Energy harvesting is performed with a magneto-inductive transducer designed to maximize the recovery in response to the vibrating input due to the impact between the shoe and the ground during walking or running. The electronics interface consists of a step-up and buck converter, and, by means of a full wave active boost converter with a transducer current control, provides an optimum adaptive load emulation independently from the signal provided by the transducer and from the voltage stored on the output capacitor. The device has been designed in according to the manufacturing requirements for a medium-large scale production and taking into account the severe environment in term of external load where it will be placed. Numerical and experimental results show the effectiveness of the developed EH step-counter device demonstrating that the energy recovered during the impact is

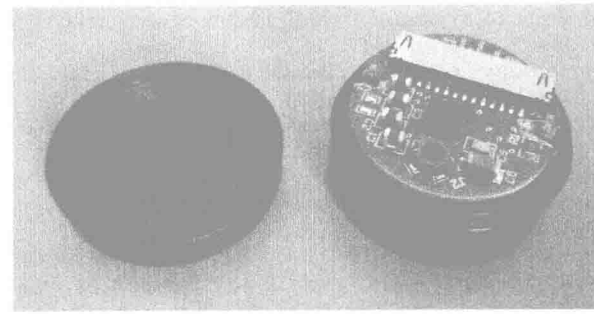


Fig. 1.11 Molded prototypes

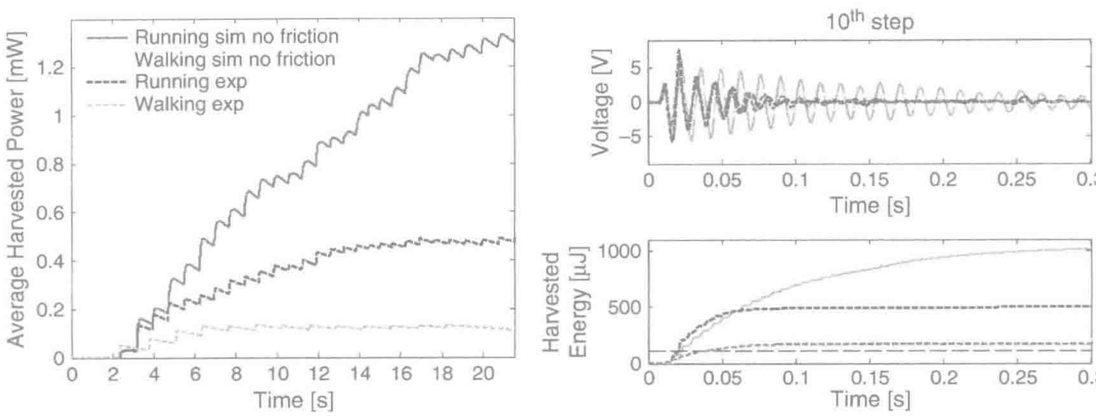


Fig. 1.12 Molded prototypes performance

maximized and it is sufficient to support the power requirement of the electronic interface allowing the step detection and the data sending also during the walking activity. Considering running activity, the harvested energy at each step is about four times the required. Storing this energy surplus compensates the difference with respect to the requirements under very low intensity input allowing detecting every step during activity.

Acknowledgment This work was performed under a research project with STMicroelectronics. The authors would like to thank Dr. Alessandro Gasparini, Dr. Stefano Ramorini and Dr. Alberto Cattani from STMicroelectronics for their enthusiasm and driving force in the project.

References

1. Shenck NS, Paradiso JA (2001) Energy scavenging with shoe-mounted piezoelectrics. IEEE Micro 21(3):30–42
2. Rocha JG, Gonçalves LM, Rocha PF, Silva MP, Lanceros-Méndez S (2010) Energy harvesting from piezoelectric materials fully integrated in footwear. IEEE Trans Ind Electron 57(3):813–819
3. Li WG, He S, Yu S (2010) Improving power density of a cantilever piezoelectric power harvester through a curved L-shaped proof mass. IEEE Trans Ind Electron 57(3):868–876
4. Moro L, Benasciutti D (2010) Harvested power and sensitivity analysis of vibrating shoe-mounted piezoelectric cantilevers. Smart Mater Struct 19(11):1–12
5. Carroll D, Duffy M (2012) Modelling, design, and testing of an electromagnetic power generator optimized for integration into shoes. J Syst Control Eng 226(2):256–270
6. Wang C, Miao D, Luk PC, Shen J, Xu C, Shi D (2010) A shoe-equipped linear generator for energy harvesting. In: 2010 IEEE international conference on sustainable energy technologies, Kandy, Sri Lanka, pp 1–6
7. Baghebani R, Ashoorirad M (2009) A power generating system for mobile electronic devices using human walking motion. Second Int Conf Comput Electr Eng 2:385–388
8. Dai D, Liu J, Zhou Y (2012) Harvesting biomechanical energy in the walking by shoe based on liquid metal magnetohydrodynamics. Front Energy 6(2):112–121
9. Nakano K, Elliott SJ, Rustighi E (2007) A unified approach to optimal conditions of power harvesting using electromagnetic and piezoelectric transducers. Smart Mater Struct 16(4):948–958

10. Beeby SP, O'Donnell T (2009) Electromagnetic energy harvesting. In: Priya S, Inman DJ (eds) Energy harvesting technologies. Springer, New York, pp 129–161
11. Tornincasa S, Repetto M, Bonisoli E, Di Monaco F (2012) Energy harvester for vehicle tires: nonlinear dynamics and experimental outcomes. J Intell Mat Syst Str 23(1):3–13
12. Tornincasa S, Repetto M, Bonisoli E, Di Monaco F (2012) Optimization of magneto-mechanical energy scavenger for automotive tire. J Intell Mater Syst Struct 23(8):2055–2064
13. Stephen NG (2006) On energy harvesting from ambient vibration. J Sound Vib 293(1–2):409–425
14. Liang J, Liao W (2012) Impedance modeling and analysis for piezoelectric energy harvesting systems. IEEE/ASME Trans Mechatron 17(6):1145–1157
15. Hooke R, Jeeves TA (1961) Direct search solution of numerical and statistic problems. J ACM 8(2):212–229
16. Bonisoli E, Canova A, Freschi F, Moos S, Repetto M, Tornincasa S (2010) Dynamic simulation of an electromechanical energy scavenging device. IEEE Trans Magn 46(8):2856–2859
17. Tornincasa S, Bonisoli E, Di Monaco F, Moos S, Repetto M, Freschi F (2011) Nonlinear dynamics of an electro-mechanical energy scavenger, vol 3, Modal analysis topics. Springer, New York, pp 339–349

Chapter 2
Issues in Experimental Testing of Piezoelectric Energy Harvesters

Paulo S. Varoto

Abstract The main goal of this article is to discuss current vibration testing procedures and their effects on the dynamics of beam type piezoelectric energy harvesters. The device is a cantilever beam partially covered by piezoelectric material with a mass at the beams free end. Governing equations of motion are derived for the harvester considering the excitation applied at its fixed boundary. Also, we consider the nonlinear constitutive piezoelectric equations in the formulation of the harvester's electromechanical model. The prototype is subjected to a series of laboratory tests in order to investigate how different testing procedures can affect the overall dynamics of the device under study. Nonlinear effects are also included in order to check their benefits on the harvester's dynamics in terms of the resulting electrical power as well as increase of usable frequency range.

Keywords Energy harvesting • Nonlinear vibrations • Piezoelectric materials • Electromechanical model • Energy scavenging

2.1 Introduction

Piezoelectric energy harvesting (PEH) has become a topic of increasing interest among several research areas as well as engineering majors, as it is the case of the aerospace and automotive industries. The possibility of converting certain amount of mechanical energy into usable electrical energy through has enabled the application of fundamental concepts from the theories of mechanical vibration and piezoelectricity in the development of new energy harvesting methodologies and devices, specially dedicated to power small electronics. Despite the difficulties just mentioned, recent contributions have shown promising results for piezoelectric energy harvesting either in employing linear [1–4] and nonlinear [5–8] modeling approaches in the mechanical to electrical conversion process or in developing new transduction and storage circuitry.

The well known cantilever beam model is probably the most commonly employed technique to model and design piezoelectric energy harvesters. In this case a metallic beam (substrate), is covered (partially or fully) by piezoelectric ceramic on both sides, forming a bimorph structure. The piezoelectric layers are connected in series or in parallel and are polled in the transverse direction in order to generate electrical signals from the bending vibrations induced to the beam by some external excitation source. The cantilever harvester is then designed to operate at its fundamental natural frequency for optimum electrical energy conversion, although in principle it can also be used to harvest energy from higher order mode shapes. The harvester's fundamental natural frequency can be tuned to a desired value by using a tip mass that is attached to the free end of the cantilever beam. The value of the tip mass is chosen such that the fundamental natural frequency of the device falls into an usable frequency range covered in most field applications (e.g. 0–100 Hz for environmental vibration signals).

From the testing viewpoint, once a prototype of a given energy harvester is available, it is subjected to a series of vibration tests, mostly in the laboratory environment in order to provide experimental data that will be used to validate the device's mathematical model. In this case, a commonly employed testing technique consists in performing transmissibility base driven tests [9]. The energy harvesting device is mounted on the armature table of an electromagnetic vibration exciter through a test fixture and the overall combined structure (harvester and fixture) is driven by an input signal that covers the frequency range of interest, that must contain at least the harvester's fundamental natural frequency. The nature of the input signal that can be used to drive the system can be selected from commonly employed excitation signals in modal and vibration testing, as it is the case of harmonic, random, pseudo-random, chirp, among others. Usually the output signals that are measured consist of the cantilever base acceleration and voltage from the piezoelectric layers, which are used to compute the harvester's voltage

P.S. Varoto (✉)
Department of Mechanical Engineering, School of Engineering of São Carlos – USP, São Carlos, SP, Brazil
e-mail: varoto@sc.usp.br

A. Wicks (ed.), *Shock & Vibration, Aircraft/Aerospace, and Energy Harvesting, Volume 9*,
Conference Proceedings of the Society for Experimental Mechanics Series, DOI 10.1007/978-3-319-15233-2_2