Mechanical Systems and Signal Processing 117 (2019) 862–878

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

A formulation for modeling levitation based vibration energy harvesters undergoing finite motion

C. Martín Saravia

Grupo de Investigación en Multifísica Aplicada, Universidad Tecnológica Nacional FRBB, CONICET, 11 de Abril 461, Bahía Blanca, Argentina

ARTICLE INFO

Article history:
Received 5 December 2017
Received in revised form 25 June 2018
Accepted 6 August 2018

Keywords:
Electrodynamics
Energy conversion
Finite elements
Magnetism
Energy harvesting

ABSTRACT

This paper presents a geometrically exact formulation for modeling electromagnetic vibration energy harvesters undergoing finite displacements and rotations. The formulation is conceived to model uniaxial harvesters that extract energy from the vibration of flexible multibody systems that are moving arbitrarily in space. The finite rotation framework is based on an updated Lagrangian procedure; the geometrically exact dynamic equilibrium equations of the harvester are written in terms of local director vectors using a material description. The resulting coupled electro-mechanical equations of motion preserve its classical one-dimensional form. Numerical tests are conducted to address the response of the harvester under specific finite displacements-finite rotations excitations.

1. Introduction

Vibration energy harvesters are attracting the attention of researchers worldwide; the current research on the subject is concerned with the study of materials, mechanisms and general design aspects together with the development of mathematical formulations to describe their physical behavior. Nowadays, the current research is focusing its attention primarily on the study of energy harvesters as autonomous sensing systems; this is probably the application where vibration energy harvesters would have its leading role. In this context, wind turbine blades, helicopter rotor blades, airplane wings, rotating machinery and car suspensions are just a few of the mechanical systems that can favor its growth. Most of these structures are flexible multibody systems that are finitely moving in space and time. A formulation for modeling electromagnetic energy harvesters which undergo finite motion still has not been developed; this is the motivation of this work.

The design of vibration energy harvesters involves the investigation of a wide range of aspects; frequency and amplitude of operation, volume, weight and cost are just a few of the many parameters that must be studied to address the overall harvester efficiency [1–7]. From all the parameters involved in the design, the nature of the excitation is one of the most important since it directly defines not only the harvester tuning, but also its structural and geometrical design [7].

The literature about electromagnetic energy harvesting devices is vast, complete reviews can be found in [8–11]. The existing mathematical formulations assume that the excitation source is not moving in space; so, the harvester only oscillates with respect to a fixed point [1–13]. However, to model a wide variety of real world situations this assumption is prohibitive; this is the case, for example, of applications involving wind turbine blades, helicopter rotor blades, car suspensions,

E-mail address: msaravia@frbb.utn.edu.ar

https://doi.org/10.1016/j.ymssp.2018.08.023
0888-3270/

human motion, etc. To accurately address these cases, it is strictly necessary to have a kinematic formulation of the harvester that allows its finite motion.

The formulation of a finite motion theory of a 1DOF energy harvester necessarily requires a finite rotation framework; unfortunately, this increases the complexity of the underlying mathematics considerably. Because of its vectorial nature, the finite displacement problem is not difficult to tackle; however, since finite rotations do not belong to a vector space, its treatment is much more involved. The noncommutativity of the finite tridimensional finite rotations impedes exploiting the additivity rules and therefore a pure vectorial framework cannot be set.

There are diverse alternatives to treat the finite rotation problem; all of them are based on a parametrization of the rotation manifold [14]. Most of the finite rotation formulations were conceived to describe the mechanics of rigid and deformable multi-bodies [15–22]; very often with the finite element method entering the picture. From all the parametrization choices, the rotation vector parametrization is particularly convenient since it retains some sort of additivity; also it can be easily coupled with the geometrically exact composite beam finite elements that are commonly used for modeling highly flexible structures [19]. This will be the approach chosen in this paper.

In view of the foregoing, this paper presents a formulation to model uniaxial harvesters that undergo arbitrary motion in space and time. The formulation is based on a vectorial Lagrangian approach; the finite rotation framework relies on a vector parametrization of the rotational operator. The magnetic force and the magnetic flux density derivative are obtained via polynomial fitting of finite element data. The formulation leads to a very compact form of the equilibrium equations. The resulting coupled electro-mechanical equations of motion preserve their classical one-dimensional form and can easily be re-casted into a state-space form. The formulation was implemented in a computational code based on a Runge-Kutta computational integrator. In order to address the response of the harvester under specific finite displacements-finite rotations scenarios, numerical tests defined ad-hoc were conducted.

2. The magnetic harvester

2.1. Architecture

It is assumed that the harvester architecture is such that the internal magnet moves linearly; there is no restriction in the harvester shape. It is also assumed that the harvester is attached to a structure that not only vibrates, but also undergoes rigid body motion. The harvester is excited by the motion of the main structure through a connection point; therefore, its response is the result of a rigid body motion plus an internal vibrational motion. The latter is responsible for the power generation and can be understood as a relative motion of the magnet with respect to the base point.

For simplicity it will be assumed that the harvester architecture is cylindrical and the central magnet (or stack of magnets) moves in the axial direction, so the harvester is said to be uniaxial; see Fig. 1.

The harvester is allowed to undergo finite motion; this implies the occurrence of simultaneous finite displacements and finite rotations. The former is simple to treat and allows a vectorial framework, while the latter is much more complex, and a non-vectorial framework must be adopted. This will be clarified in the following.

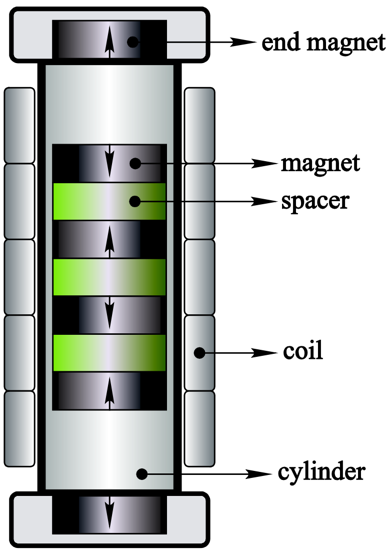

Fig. 1. Energy harvester architecture.