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STONEHENGE — Suite for nonlinear analysis of energy harvesting systems

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ABSTRACT

STONEHENGE is a toolbox designed to evaluate nonlinear vibration-based energy harvesting systems, which demand careful studies regarding their nontrivial behavior. It is composed of an ensemble of codes to study and characterize the dynamic behavior, as well as deal with varieties of physical parameters and excitation. For this, it has six modules, initial value problem, dynamic animation, nonlinear tools, sensitivity analysis, stochastic simulation, and chaos control. A bistable oscillator is used as a benchmark for a vibration harvester. We hope this toolbox can contribute to the development and improvement of old and new generations of nonlinear vibration-based energy harvesting systems.

Code metadata

Current code version	*v1*
Permanent link to code/repository used for this code version	https://github.com/SoftwareImpacts/SIMPAC-2021-133
Permanent link to reproducible capsule	https://codeocean.com/capsule/4891890/tree/v1
Legal Code License	*MIT license*
Code versioning system used	*git*
Software code languages, tools, and services used	*Matlab and C++*
Compilation requirements, operating environments & dependencies	*UQLab - Matlab*
If available Link to developer documentation/manual	https://github.com/americocunhajr/STONEHENGE
Support email for questions	jp.norenberg@unesp.br

1. Introduction

Vibration-based energy harvesting systems convert kinetic energy dispersed in the environment into electricity [1]. These systems aim to be self-powered low-consumption electromechanical devices used in several applications such as sensors, medical implants, etc. [2,3]. Nonlinear harvesters have been shown to be an efficient alternative in broadband frequency applications of energy harvesting [4–6]. However, they are complex dynamical systems that require detailed analysis for innovative design and optimal configurations. To address this issue, we present STONEHENGE, an ensemble of codes developed to conduct nonlinear analysis on a vibration piezoelectric-magneto-elastic energy harvester [7]. The goal of STONEHENGE is to solve complex problems involving vibration-based energy harvesting systems, support the functioning of numerical experiments, and extracts knowledge from the nonlinear models. We hope this toolbox can serve the research community (and maybe the industry) to facilitate the conception and analysis of vibration-based energy harvesting systems and their application in

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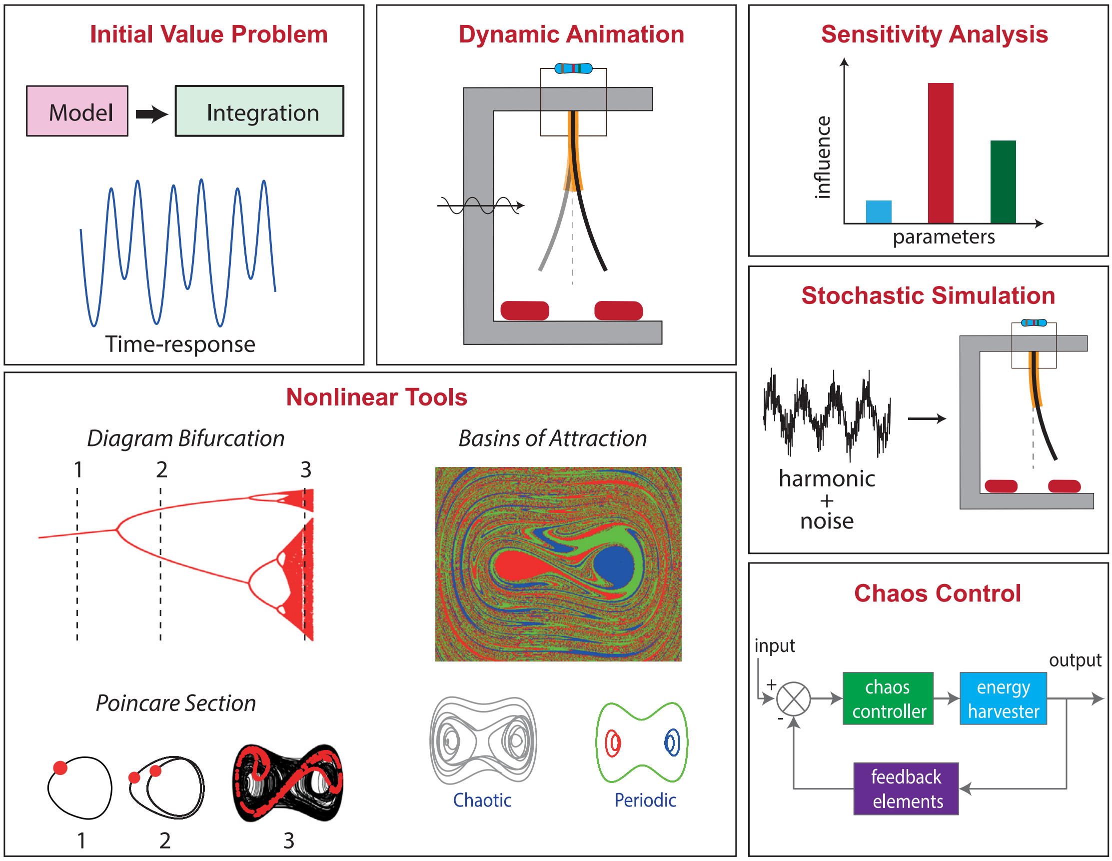

Fig. 1. Schematic representation of the STONEHENGE package modules.

real-world problems. For this, STONEHENGE offers a didactic ensemble of codes to operate. A schematic representation of the package modules is available in Fig. 1.

2. Software details

STONEHENGE provides a comprehensive toolbox for energy harvesting systems assessment, encompassing an initial value problem (IVP) solver; a visualization module to see animations of the system dynamics; nonlinear analysis tools such as Poincaré section, bifurcation diagram, and basins of attraction; a global sensitivity analysis module; a stochastic dynamic simulator; and control of chaos simulator. The package is a didactic and intuitive tool, written in Matlab and C++ languages. The suite source code can be found in a GitHub repository,[1] as well as the user manual with more details. Each module in the package is briefly described below.

Initial Value Problem: In the IVP module it is possible to integrate the system dynamics, evaluate time-series responses such as displacement, velocity, and voltage, and thus analyze the dynamics on the time domain. The instantaneous power can be also obtained with aid of this module. In [8,9] the authors use time series analysis to assess the effects of excitation amplitude and frequency on the harvester.

Dynamic Animation: The animation module is a great and novel tool applied to energy harvesting systems, able to dynamically visualize the physical motion of the electromechanical system, based on information extracted from numerical simulations. Some video animations obtained with this module are available in the GitHub repository see footnote 1 and YouTube channel.[2] They are mentioned in the following publications [10,11]. To the best of our knowledge, these are the only works in the open literature showing this type of animation for a nonlinear vibrating harvester, an innovation in the way of studying the dynamics of this type of system.

Nonlinear Tools: Due to nonlinear characteristics, this system can present complex responses, which require meticulous attention for its understanding and application. In this way, STONEHENGE handles three tools for understanding the system nonlinearities, the Poincaré section, bifurcation diagram, and basins of attraction. These modules allow us to characterize the dynamic response as periodic or chaotic and map its sensibility concerning the initials conditions. In [8,9], bifurcation analysis is carried out to identify excitation conditions that lead to chaotic behavior, while [12,13] employ the basins of attraction to study behavior under different initial conditions. These studies possibly contain the largest collection of basins of attraction in the open literature (a few dozen). Due to the high computational cost of these calculations, it is common for authors to only provide one or two figures with this information. Such a broad study was only possible because the basin module was implemented aiming to be computationally efficient.

Stochastic Simulation: It is noteworthy that excitations in environment sources are subject to noise. So, the stochastic simulation module deals with the underlying system subjected to a harmonic excitation disturbed by Gaussian colored noise. Several scenarios through Monte Carlo simulation are generated for the system behavior, and patterns are extracted by statistical methods. The Ref. [14] presents the results of time series and statistical analysis of the bistable harvester under the effect of these colored noise disturbances.

Sensitivity Analysis: The sensitivity analysis module investigates the effect of parametric variabilities on the system response. It is a powerful statistical tool to understand the influence of parameters on the energy recovering process. Therefore, this module can indicate

[1] https://github.com/americocunhajr/STONEHENGE.
[2] https://youtube.com/playlist?list=PLjNDdMKtfqVmcawBUvQvKOGcbHvB507On.

which parameter most affects the system response, a piece of essential knowledge to better understand the underlying physical phenomenon (which parameters may compromise the energy harvesting process); prototype design (which parameters require greater precision in manufacturing, for instance); and robustness and optimization studies (which parameters increase the generation slightly affecting its magnitude). In [10,12] the authors present, in detail, the sensitivity analysis for bistable energy harvesting systems with and without asymmetries. These are the first studies with global sensitivity analysis in nonlinear harvesters, bringing new insights to the literature about their dynamic behavior.

Chaos Control: This module implements two strategies for chaos control on the energy harvesting dynamical system: (i) the OGY method; (ii) an digital version of the extended time-delay feedback method. The goal is to stabilize the chaotic behavior, obtaining a power time series that is more fruitful for a possible signal treatment (for posterior use) and power harvesting. Control strategies to deal with chaotic configurations, and so, improve the harvested power, are proposed in [15,16]. In addition to this topic still being little explored in the energy harvesting literature, the extended-delay feedback controller is possibly the first digital controller (an essential feature for field or laboratory implementation) to appear in the literature, certainly contributing to broadening the horizons of chaos control in energy harvesting.

3. Impact overview

STONEHENGE emerged from the research work related to the nonlinear analysis of energy harvesting systems developed by Rio de Janeiro State University (UERJ) and the State University of São Paulo (UNESP), and has been proving to be a very robust tool for different tasks such as: (i) evaluate the efficiency of the energy harvesting process; (ii) obtain a better comprehension of the dynamic system behavior; (iii) take design decisions. Several of these aspects are observed in [11], which combined accumulated insight from these analyzes and a state-of-the-art optimization tool to find nice configurations of design parameters that allow maximizing the power recovered by the bistable harvester.

Despite being a user-friendly toolbox, easily customizable to other models, all these codes are implemented to address bistable energy harvesting models, defined by a system of ordinary differential equations. To adapt these modules to deal with other nonlinear harvesters, it is necessary to implement small modifications in the source codes, changing the differential equations. In the future, the authors plan to further improve STONEHENGE by focusing on implement new modules, such as uncertainty quantification, parametric optimization, and experimental validation techniques.

4. Final remarks

STONEHENGE is an extensive package that provides a framework for analysis of vibration-based energy harvesting systems, which allow to study and characterize its dynamic behavior, as well as to carry out statistical analysis, comprising which uncertainties sources, from environment and manufacturing process, requires more attention. We believe that this toolbox may have an impact and help advance the research and application of vibratory harvesters both, in the research community and the industry.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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