Simulation Modelling Practice and Theory 81 (2018) 1–10

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

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

Parameter estimation of nonlinear thermoelectric structures using particle swarm optimization

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ARTICLE INFO

Article history:
Received 25 July 2017
Revised 7 November 2017
Accepted 12 November 2017

Keywords:
Energy Harvesting
Thermoelectric module
PSO algorithm
Genetic algorithm
Simulated annealing
System identification
Nonlinear LQG controller
Thermal controller for PCR cycling
Parameter estimation
Optimization

ABSTRACT

The purpose of this investigation is motivated mainly for thermal energy harvesting devices and temperature feedback controllers interacting with electronic circuits. Mostly intended to design Linear Quadratic Gaussian (LQG) type controllers, suitable for uncertain dynamical systems, in which not all state variables are measured and available for proper feedback. We present a methodology for modeling and estimation of several internal parameters for a proposed thermal characterization apparatus that employs thermoelectric modules (TEMs). Repeated random vector sampling, similar to Monte Carlo method, is combined with particle swarm optimization (PSO) algorithm for parameter estimation. For the intended applications, is mandatory to drive apparatus that have embedded TEMs, not only using direct current powering, as usually done in literature, but also with alternate current signals over a large range of relevant frequencies. For exciting the many nonlinear and linear states during the identification procedure, a single embedded TEM is injected with a proper random electrical current signal having power spectral density of a band-limited white noise. Sensitivity to both initial conditions and different sets of random excitation, brings uncertainty in the estimated 21 parameters of our mechanical apparatus with two embedded TEMs and their corresponding dynamics. Simulation are presented showing the effectiveness of the proposed estimation technique, with convergence performance and parameter statistical distribution over a set of uncorrelated random current vector excitation.

1. Introduction

The lack of fossil fuels and the uncontrolled increase of world carbon emissions have attracted a considerable attention of society and researches in general. More specifically, many research teams are working in the area of alternative energy conversion methods like solar and wind power generation. These methods are becoming progressively more efficient, however, there are specific circumstances making their maintenance costs unattractive. On the other hand, solid-state thermoelectric converters are an environmentally friendly energy source and it is quite attractive when compared with other production technologies of small quantities of electric power, especially when applied in remote areas or when the usual renewable energy sources are not regularly available [1].

Easy adaptation and structure without moving parts make the use of TEMs in constant rise, especially in sustainable heating and cooling systems [2], but its low efficiency when compared with conventional electric coolers and generator

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https://doi.org/10.1016/j.simpat.2017.11.004
1569-190X/

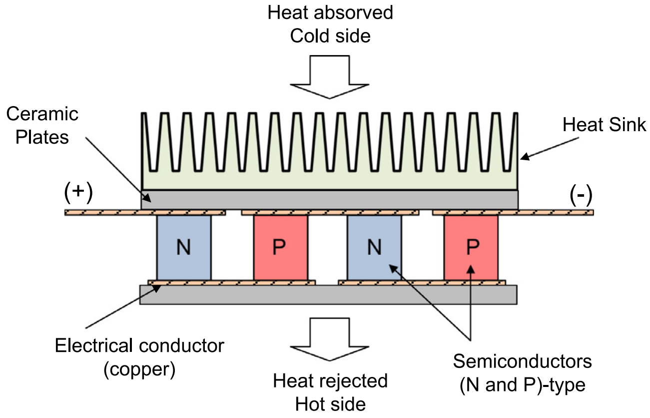

Fig. 1. Cross-sectional diagram of a TEM.

is, at the current state-of-art, a major disadvantage. However, nowadays the reduction in size and power consumption of consumer electronics has opened up many new opportunities for ultra low voltage conversion technologies, the design of thermal energy harvesting circuits for sensor networks [3–5] and the development of complete autonomous powering devices based on thermoelectric generation. Precise temperature control for thermal characterization is also of great interest [6,7].

TEMs consist of N pairs of semiconductors pressed between two ceramic plates as shown in Fig. 1. When used to obtain a desired temperature profile for material characterization, it is necessary to design precise temperature controllers, which may require a state estimator of internal variables, not accessible by sensors. Thus, it is essential to develop techniques and models that represent the correct TEM behavior to control temperature changes by varying the applied electrical current. The time scale usage of the device under characterization, along with the types of both the signal excitation and surrounding disturbances, require great deal of attention. They determine whether the model should be a steady-state one or needs the multiple dynamical modes involved. For example, small actuators built with vanadium dioxide explore a thermally induced solid-to-solid phase transition, which exhibits a temperature-dependent hysteresis [8]. To control that kind of actuators, a very accurate and complex temperature excitation profile is required to obtain a proper device characterization. A controller to perform well for such requirements demands the knowledge of the TEM's transient behavior and its internal states or parameters. On the other hand, the use of TEMs for powering sensors [2] presumes temperature gradients which are slowly variant in time. For this last case, the primary focus is to evaluate the TEM's process of energy conversion under different but fixed temperature gradients; and a steady-state model requires no further electro-thermal dynamical investigation. The present identification methodology is intended to obtain the sensitivity analysis or statistical dispersion of estimated parameters, which inherently affects and may provide the level of uncertainty in state estimators for LQG-type or MPC (Model predictive control) controllers. This type of analysis is often used to tune calibration functions of the estimated parameters, to reduce model discrepancy due to underlying missing physics or numerical approximations.

There are possible benefits for the two categories of modeling usually employed in our type of device, parametric and non-parametric. The non-parametric modeling makes minimal or no *a prior* assumptions for the model structure [9]. When considering only TEMs, the underlying physical behavior is well-known, and there is plenty availability of knowledge regarding phenomenological models, mostly available in the literature.

We derived a model for a project design of an experimental set-up with features usually found in many applications for which our uncertainty analysis is relevant. Using available *a priori* knowledge and expressing the identification problem as parametric modeling, we transformed the methodology to a parameter estimation procedure. Nevertheless, many different sets of solutions may arise in nonlinear parametric identification technique, according to the mathematical modeling of the system to be identified. This situation is similar to estimating linear systems using least-squares method when the normal matrix is near singular. The possibility of obtaining irrelevant or inconsistent parameters values for nonlinear models involving TEMs is not yet established in the literature.

Near future TEM devices may change their current behavior, as the discovering example of stronger cooling effects at graphene contacts [10]. As a consequence of these continuous changes in technology, nonlinear identification may lead to substantial error in estimated parameters, even when a mathematical model contains the most essential characteristics of the physical system [11]. Our proposed model, with fixed and previously known parameters, has the rule of a reference experimental data, and we call it the *Real Model*. The structure of the identification model, for the purpose of comparison, is exactly the same of the *Real Model* and we call it the *Estimated Model*.

This paper is intended to explain the use of PSO for estimation of static and dynamic parameters of a mechanical apparatus with two embedded TEMs, by using just one temperature measurement, as shown in Fig. 2. The parameter estimation method is here defined as a minimization problem of the mean squares error between the temporal temperature behavior