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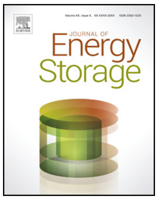

# Genetic optimization and experimental validation of a test cycle that maximizes parameter identifiability for a Li-ion equivalent-circuit battery model

Michael J. Rothenberger, Donald J. Docimo, Mohammad Ghanaatpishe, Hosam K. Fathy*

*Department of Mechanical and Nuclear Engineering, Pennsylvania State University, 157D Hammond Building, University Park, PA 16802, United States*

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ABSTRACT

This article presents an experimental study demonstrating the degree to which optimal experimental design can improve lithium-ion battery parameter estimation. The article is motivated by previous literature showing that lithium-ion batteries suffer from poor parameter identifiability. This makes it difficult to estimate battery parameters quickly and accurately from input–output cycling data. Previous research shows that optimizing the shape of a battery cycle for Fisher information – an identifiability metric – can improve parameter estimation speed and accuracy significantly. However, most studies demonstrating this improvement are simulation-based, rather than experimental. In contrast, the centermost goal in this article is to provide an experimental assessment of the degree to which trajectory optimization for Fisher identifiability can improve lithium-ion battery parameter estimation. We optimize battery cycling to maximize Fisher information for a nonlinear second-order model of a commercial lithium iron phosphate (LFP) cell. We implement this optimal cycle experimentally for 3 different battery cells, and compare it with two benchmark cycles representing automotive battery use. The results of this comparison are quite compelling: when parameterized using data from the optimal cycle, the cell voltage prediction signal-to-noise ratio improves significantly over the benchmarks. Moreover, only the optimized cycle produces reasonable estimates of battery parameters over the course of a 4-hour experiment.

## 1. Introduction and literature review

This article presents an experimental study examining the extent to which input trajectory shaping for identifiability maximization can improve parameter estimation for an equivalent-circuit lithium-ion battery model. The article is motivated by the well-recognized challenge of parameter identifiability in lithium-ion batteries: a challenge that often makes it difficult to estimate battery parameters quickly and accurately from experimental data. More specifically, the article is motivated by the fundamental conjecture that the optimal design of a battery test cycle can improve its parameter identifiability, and therefore the speed and accuracy with which its parameters can be estimated. Existing research in the literature supports this conjecture, mostly using simulation studies. Our goal, in contrast, is to examine this conjecture experimentally. Specifically, we use a genetic algorithm to obtain a battery charge/discharge trajectory that maximizes Fisher information—a parameter identifiability metric. We restrict this optimization to periodic current trajectories, but the underlying approach is broadly applicable to other types of trajectories. Two benchmark cycles are used for comparison, both of them representing automotive battery utilization scenarios. The overarching goal is to compare the parameter estimation results for the optimized cycle vis-à-vis these benchmarks.

Broadly speaking, the term “identifiability” refers to the solvability of the problem of estimating a model's parameters from experimental input–output data. Challenges associated with identifiability can be classified into two groups: *structural* challenges and *numerical* challenges. When a model suffers from poor structural identifiability, this means that it is mathematically impossible to estimate its parameters uniquely from experimental data [1]. This can arise in electrochemical battery models if such models have redundant parameters: a fact illustrated by Sitterly et al. [2]. In such a scenario, it is only possible to estimate combinations of the battery model’s parameters, rather than the parameters themselves. In contrast, when a model suffers from poor *numerical identifiability*, this means that the problem of estimating the model's parameters from experimental data is

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* Corresponding author.
*E-mail address:* hkf2@psu.edu (H.K. Fathy).

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solvable, but ill-conditioned. This can make it very difficult to estimate the parameters quickly and accurately from experimental data. Numerical identifiability issues can arise in higher-order battery models: a fact illustrated by Hu et al. [3]. Such models are more likely to be over-parameterized, to the point where the problem of estimating their parameters from experimental data may be ill-conditioned. Numerical identifiability issues can also arise because of poor experimental design: a fact highlighted in previous work by Sharma and Fathy [4]. In that situation, the way that the given battery is cycled does not excite the underlying dynamics sufficiently to enable fast and accurate parameter estimation [5,6]. The existence of both structural and numerical identifiability issues in lithium-ion battery models is well-documented in the literature for a broad range of models, including single-particle models [7–10], porous quasi 2-dimensional physics-based battery models [11], and even simple equivalent circuit battery models [4].

The literature addresses the challenge of numerical battery identifiability using the tools of optimal experimental design, including input trajectory shaping techniques. Forman et al. [12], for instance, maximize the identifiability of parameters for a battery health degradation model by optimizing the parameters of the constant current/constant voltage (CCCV) suite of tests used for parameterizing this model. For electrochemical battery model parameters, Zhang et al. [13] optimize identifiability in a piecewise manner to maximize the identifiability of as many parameters as possible in each “piece” of an overall experiment. Similarly, Marcicki et al. [14] partition the overall exercise of estimating a battery model's parameters into a sequence of experiments, each of them enabling the accurate estimation of a subset of the overall parameter set. All of the above studies involve estimating battery parameter sets using a suite of experiments. In contrast, Sanchez et al. [15] use input shaping of a single trajectory to determine the analytic optimal solution for parameter identifiability of a linear impedance model. Optimizing a battery testing experiment for parameter identifiability often furnishes aggressive experiments that are more likely to induce battery aging, degradation, and damage. Forman et al. [16] address this challenge formally by using trajectory shaping to create a Pareto front comparing electrochemical battery parameter identifiability against the degradation caused by the identification cycle. Finally, previous research by this article’s authors uses input shaping for Fisher identifiability optimization of a nonlinear equivalent-circuit battery model [17]. The numerical results from that study highlight the dramatic identifiability improvements that can be obtained through input shaping when compared against electrified vehicle current demand profiles.

The existing literature on optimal experimental design for battery identifiability is very encouraging in the sense that it shows significant improvements in parameter estimation, but most of the studies it contains are simulation-based. In contrast, the main contribution of this article is an experimental assessment of the degree to which optimal experimental design for identifiability can improve battery parameter estimation. Specifically, the article shapes a periodic input current profile to maximize the parameter identifiability of a nonlinear second-order equivalent-circuit model of a commercial lithium iron phosphate (LFP) cell. This is a non-convex optimization problem: a challenge we address through genetic optimization. We apply the resulting optimized test cycle to three different battery cells. Moreover, we compare the resulting battery parameter estimates against two benchmark cycles representing automotive battery use. The use of automotive cycles as benchmarks is important for two reasons. First, it provides a baseline level of parameter estimation speed and accuracy representing the limits of *online* parameter estimation and diagnostics. Second, the literature already presents research where automotive benchmark cycles are used *in the laboratory* for battery parameter estimation and degradation modeling [18–22]. The results of this experimental comparison are very encouraging: they show a much better cell voltage prediction signal-to-noise ratio for the optimal cycle (compared to the benchmarks). Moreover, only the optimized cycle is able to produce reasonable battery parameter estimates during a 4-hour timeframe. The value of this article lies both in this experimental validation and in the fact that its approach is easily generalizable to other test cycles, models, and battery chemistries.

The remainder of this article is organized as follows. Section 2 presents the formulation of the input trajectory optimization problem. Section 3 outlines the genetic algorithm used for solving this optimization problem, and analyzes Fisher information for the optimal and benchmark cycles. Section 4 describes the experimental setup. Section 5 describes the method used for estimating battery parameters from experimental data. Section 6 presents and discusses the results of this experimental estimation study. Finally, Section 7 concludes the paper with a brief summary of the presented work.

## 2. Optimization problem formulation

To optimize a battery’s input current trajectory for parameter identifiability, one needs: (i) a battery model, (ii) an identifiability metric, and (iii) an optimization problem statement that brings together the model, the identifiability metric, and optimization constraints. This section presents a 2nd-order equivalent-circuit model used for identifiability optimization. The model has linear state dynamics plus a nonlinear voltage output equation. The section then presents the Fisher information matrix, and its use for quantifying this model’s parameter identifiability. Finally, we present an optimization problem where the goal is to maximize the determinant of this Fisher information matrix subject to several important cycling constraints.

### 2.1. Equivalent-circuit battery model

The optimization study employs a 2nd-order equivalent circuit battery model, presented in Fig. 1. This model has a nonlinear relationship between open-circuit voltage (OCV) and state of charge (SOC). The state space representation of this nonlinear system is given as:

$$\dot{x}_1 = \frac{1}{Q}u, \quad \dot{x}_2 = -\frac{1}{R_1 C_1}x_2 + u \tag{1}$$

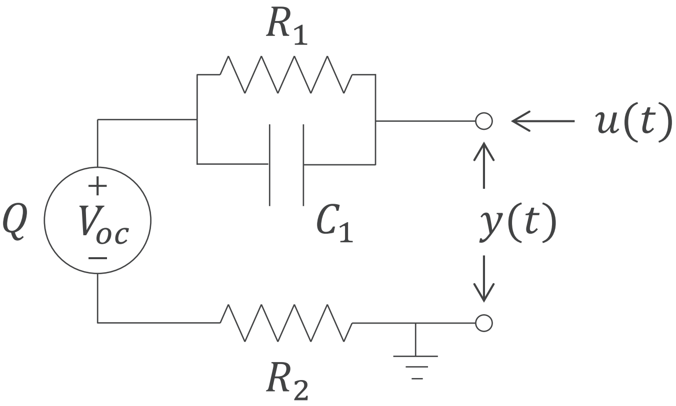

**Fig. 1.** 2nd-order nonlinear equivalent-circuit battery model.