

Application of POD plus LTI ROM to Battery Thermal Modeling: SISO Case

Saeed Asgari, Xiao Hu, and Michael Tsuk
ANSYS Inc.

Shailendra Kaushik
General Motors Co.

ABSTRACT

The thermal behavior of a fluid-cooled battery can be modeled using computational fluid dynamics (CFD). Depending on the size and complexity of the battery module and the available computing hardware, the simulation can take days or weeks to run. This work introduces a reduced-order model that combines proper orthogonal decomposition, capturing the variation of the temperature field in the spatial domain, and linear time-invariant system techniques exploiting the linear relationship between the resulting proper orthogonal decomposition coefficients and the uniform heat source considered here as the input to the system. After completing an initial CFD run to establish the reduction, the reduced-order model runs much faster than the CFD model. This work will focus on thermal modeling of a single prismatic battery cell with one adjacent cooling channel. The extension to the multiple input multiple output case such as a battery module will be discussed in another paper.

CITATION: Asgari, S., Hu, X., Tsuk, M., and Kaushik, S., "Application of POD plus LTI ROM to Battery Thermal Modeling: SISO Case," *SAE Int. J. Commer. Veh.* 7(1):2014, doi:10.4271/2014-01-1843.

INTRODUCTION

The Hybrid Electrical Vehicles (HEV) and Electrical Vehicles (EV) utilize battery thermal management and control systems in order to guarantee a minimum battery life. As a result, modeling the battery thermal behavior is very important to many automobile manufacturers.

In order to do this, CFD tools such as ANSYS Fluent may be used. However, depending on the size, complexity of the battery module and the available computing hardware, this can take days and weeks to finish and even become impractical. Therefore, reduced order modeling (ROM) and system modeling techniques are often used to help solve these problems. The focus of this work is on thermal modeling where a uniform heat source is applied to the battery cell and the temperature distribution is approximated by a ROM.

The method of proper orthogonal decomposition (POD) combined with the numerical strength of singular value decomposition (SVD) [2] provides useful insight into compact representation of temperature field. On the other hand, it can be shown that the heat diffusion equation, see [Appendix A](#), has an equivalent state-space linear time-invariant (LTI) representation. For these reasons, the POD plus LTI ROM is introduced in order to approximate the thermal behavior of the battery cell unit while also including the spatial information.

Thus, using an appropriate set of uniform constant heat source excitations, a set of temperature snapshots are collected, for example, from a CFD simulator such as ANSYS Fluent and saved into an observation matrix obtained from modeling of the battery cell unit. Then, the POD [2], [3] and [5] is used by the application of SVD to the observation matrix, approximating the temperature field, as a linear span of two separable functions [2]. One that is entirely a function of time referred to as POD coefficients. The other that is entirely a function of space referred to as POD orthonormal basis.

The paper is organized as follows. In [Section II](#), we will introduce and discuss the combined POD and LTI ROM techniques for battery thermal modeling in more detail. In [Section III](#), we will go over two examples showing the strength of the POD plus LTI ROM techniques working together to approximate the temperature distributions of a battery cell with liquid cooling. In [Section IV](#), we conclude and discuss future extensions.

II. THE POD PLUS LTI ROM

In this section, we will discuss the POD plus LTI ROM approach for thermal modeling of the battery cell. In this paper, we introduce the algorithm for a single input and single output

(SISO) battery cell scenario. Figure 1 shows the state-space LTI fit to a step response of a battery cell next to a cooling channel [1].

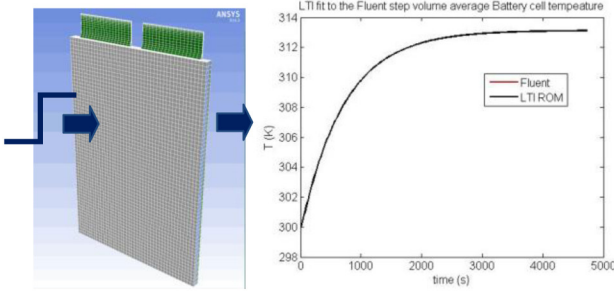


Figure 1. The LTI approximation to volume averaged temperature of one-cell unit [1].

The relationship between a uniform heat source and (volume) average temperature of a battery cell can be described by a LTI system [1]. Even though the technique described in [1] can be used to approximate the (volume) average temperature of the battery cells with very good accuracy and robustness, the average temperature does not reveal where the hot spots on the battery cells are. As a result, a ROM technique that can approximate the temperature distribution is needed.

The following algorithm describes the POD plus LTI ROM approach in the SISO case:

1. Use the method of snapshots [2] to generate the POD for the thermal (step) responses, $T(x, y, z, t)$, obtained from ANSYS Fluent transient simulations:

$$T(x, y, z, t) \cong \sum_{i=1}^N \lambda_i(t) \phi_i(x, y, z) \quad (II. 1)$$

where $\lambda_i(t)$ are the POD coefficients, i.e., the only terms that are dependent on the uniform input heat source $q(t)$ and $\phi_i(x, y, z)$ which are the (reduced) orthonormal basis.

2. Provide a state-space LTI, $[A, B, C, D]$, approximation to the reduced POD coefficients $\lambda_i(t) \forall i \in \{1, \dots, N\}$ for example using the technique described in [1]. This means

$$\lambda_i(t) \cong \int_0^t h_i(t - \tau) q(\tau) d\tau \quad (II. 2)$$

where for relaxed LTI systems

$$h_i(t) = [C e^{At} B + D \delta(t)]_i \quad (II. 3)$$

are the state-space impulse responses and

$$q(t) \xrightarrow{[A, B, C, D]} \begin{bmatrix} \lambda_1(t) \\ \vdots \\ \lambda_N(t) \end{bmatrix}_{\underline{\lambda}_N(t)} \Rightarrow \dot{X}(t) = AX(t) + Bq(t)$$

$$\underline{\lambda}_N(t) = CX(t) + Dq(t)$$

(see Appendix A) $\delta(t)$ and is the Dirac delta function. The $\rightarrow$

above describes the LTI relationship between the uniform heat source $q(t)$ and POD coefficients $\lambda_N(t)$.

3. The POD Plus LTI ROM is composed of $[A, B, C, D]$ and $\phi_i(x, y, z) \forall i \in \{1, \dots, N\}$.

Step 1 above can be obtained by applying a uniform constant heat source to the battery cell of Figure 1 for several time steps and saving the temperature profile at each time step as columns of an observation matrix Z . The SVD of the observation matrix Z can then be expressed by (II. 1).

Thus, let $z_k = [T(x_{k'}, y_{k'}, z_{k'}, t_1) \dots T(x_{k'}, y_{k'}, z_{k'}, t_M)]$ be the k^{th} row of the observation matrix Z where $\{t_1, \dots, t_M\}$ are the time samples corresponding to each column of the observation matrix then $[U, \Sigma, V] = \text{svd}(Z)$. The singular values are ordered as the diagonal elements, in descending order, of the diagonal matrix Σ . The reduced basis can be obtained by choosing a maximum of N terms that preserve a relative amount of energy in the representation. As a result, in (II. 1),

$$\lambda_i(t)_{t=t_1 \dots t_M} = \left[\sum V^T \right]_i \quad \forall i \in \{1, \dots, N\}$$

$$\phi_i(x_k, y_k, z_k)_{k \in \{1, \dots, K\}} = U(\dots, i, \dots)$$

where $U(\dots, i, \dots)$ is the i^{th} column of U , K is the total number of control volume discretization samples and superscript T stands for transpose.

The POD plus LTI then is composed of the reduced POD basis, matrix $U_N = U(:, 1 : N)$, and MATLAB notation was adopted here, along with the state-space LTI, $[A, B, C, D]$ which approximates the POD coefficients. Since the proposed ROM is generated using the SVD of the observation matrix, composed of different temperature snapshots, we would like to also alternatively refer to this technique as SVD plus LTI ROM.

Remark II.1

The direct coupling, D , term is negligible and can be ignored in practice.

To construct and approximate the battery cell temperature distribution for a time-varying, but still spatially uniform, heat source, the arbitrary heat source is convolved with the LTI impulse response obtained from state-space representation according to (II. 2) and (II. 3). Alternatively, any time-stepping algorithm with an ordinary differential equation (ODE) solver, available with multi-physics simulation tools such as ANSYS Simporer, can be used. Once the POD coefficients are approximated, from (II. 1), using the (reduced) basis U , the cell temperature distribution can be approximated.

In practice, the heat source itself is also a function of temperature. Assuming the relationship between heat source and temperature can be extracted from measurement by some fitting algorithm, the techniques presented in this work can be extended to handle the case where the heat source itself is temperature dependent.

This is done by first finding the POD plus LTI ROM relationship as discussed in this section. Next, knowing the descriptive dependence of heat to temperature, found via some extraction method, one can solve for the temperature field by tightly coupling the heat source to temperature performed during the consumption of ROM.

That means at every time step, the POD plus LTI ROM will provide an approximation to the temperature field. Then the (volume) averaged temperature can be used as input to the descriptive model of heat as a function of temperature to calculate the corresponding heat at that time step. The calculated heat at previous time step then will be used as a new input to the POD plus LTI ROM and this process continues.

As an example, an electrical circuit model (ECM) [4] of the battery's electrochemical behavior can be used. The nonlinear resistors and capacitors of the ECM are not only a function of battery's state of charge (SOC) but also (volume) average temperature rise in the battery cell. The ECM will provide the uniform heat source used as input to the POD plus LTI ROM.

Remark II.2

At each time step the POD plus LTI ROM will approximate the temperature distribution of the battery cell. However, since the heat source is assumed uniform in this work, the average temperature is used with the ECM.

In the next section, we will demonstrate the approach on an example system.

III. SIMULATION RESULTS AND DISCUSSION

The following example considers a SISO case with thermal boundary conditions imposed on the battery cell. Figure 2 shows a battery cell next to a liquid cooling channel with a fixed mass flow rate, i.e., a SISO case.

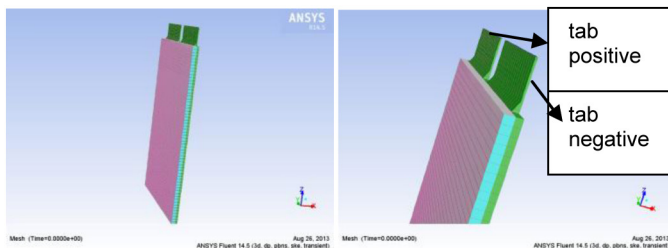


Figure 2. a) One cell with liquid cooling channel next to it. b) zooming in.

The following table summarizes the thermal boundary conditions (BC) on the one-cell unit model used here to perform exploration study of the application of POD plus LTI ROM while including thermal BC on the positive and negative tab solid cells:

Table 1. Thermal BC on the tab positive and negative with room temperature set at 300 degree Kelvin (K).

Battery zone	Convection BC heat transfer coefficient $\left(\frac{\text{Watts}}{\text{m}^2\text{K}}\right)$	Free stream temperature (K)
Tab Positive	1000	350
Tab Negative	1000	350

The thermal BC on the tabs, as shown in Table 1, are chosen significant enough to ensure their effects are included while POD plus LTI ROM goes to work. The POD plus LTI ROM approach has been applied and the results are shown step by step. The POD plus LTI ROM algorithm, as discussed in Section II, has been applied to the example shown in Figure 2.

Figure 3 a) shows the result of SVD on the observation matrix and selection of the number of orthonormal basis vectors based on a user-specified threshold of 10^{-6} on the relative energy contributions of singular values.

Figure 3 b) shows the LTI fit to the first four dominant POD coefficients using the method described in [1].

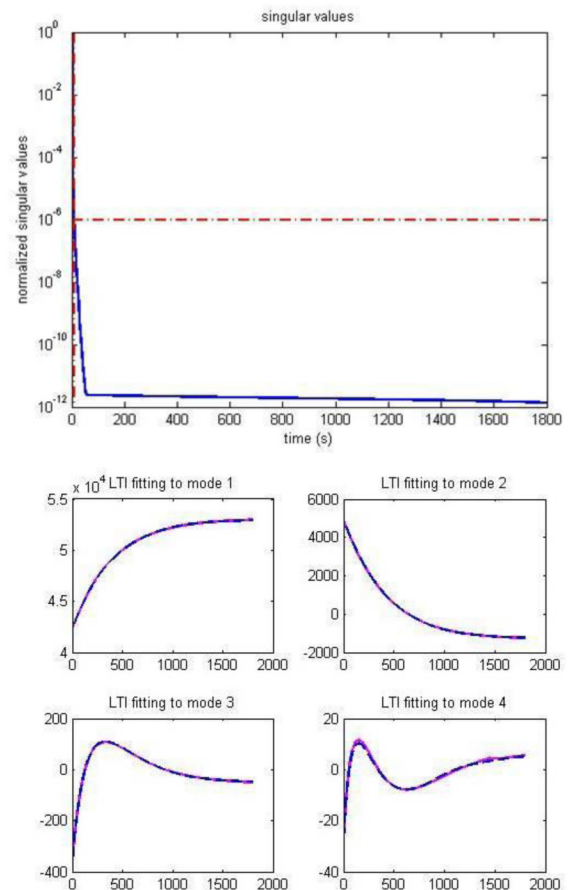


Figure 3. a) (Top) Using a threshold of 10^{-6} will result in four reduced basis vectors. b) (Bottom) LTI fits to the first four dominant coefficients.