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The characterization of dynamic behavior of Li-ion battery packs for enhanced design and states identification

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ABSTRACT

The dynamic responses of a Li-ion battery pack deployed on hybrid electric vehicles are studied with a high fidelity finite element model and a parametric reduced-order model. The effects of microstructure transformation in the electrode materials caused by lithium-ion intercalation/deintercalation on the evolution of dynamic responses are investigated including the effects of the state of charge, aging, and cell-to-cell variations. The dynamic responses obtained from a finite element analysis show two interesting phenomena. First, the high modal density is controllable with the design modification of a pack component. Second, dynamic responses, especially the evolution of the natural frequencies of the fixed-boundary modes, of a Li-ion battery pack provide useful information to estimate the dynamic states or health states of the battery. A probabilistic analysis is also carried out considering stochastic operational conditions of hybrid electric vehicles with a parametric reduced-order model. The probabilistic analysis not only suggests appropriate modes and locations for monitoring its dynamic responses, but also determines the maximum response level of every cell in the battery pack. The proposed modeling approach can improve the safety and reliability of the structural design of battery cells and packs. Furthermore, it can be useful for the identification of the battery states during the operation.

1. Introduction

Li-ion Batteries (LIBs) are free from several deficiencies that occur in other secondary cells, such as high self-discharge rates [1] and memory effect [2]. LIBs also have a higher energy economy than other secondary batteries [3]. These advantages enable LIBs to dominate the portable electronics market and establish them as promising reversible power sources for electric powered vehicles [4].

The lifespan and aging [5] of LIBs are major concerns that limit their application in the electric transportation markets. To ensure the lifespan of LIBs during operation, significant efforts have been devoted to two research areas. The first area is focused on optimization of the design of battery cells and packs. The second area is focused on development of enhanced control methodologies embedded in the battery management system.

Mechanical stresses from Li-ion intercalation and temperature variation should be considered in the design of LIBs. Dynamic and accumulated stresses affect performance and degradation of LIBs [6].

Several studies on mechanical characteristics of LIBs have been conducted. Anode swelling was measured and correlated with microscopic lattice expansion of graphite to elucidate the swelling mechanism [7]. An image processing technique used optical images to observe reversible strains during lithiation of a graphite electrode [8]. Neutron radiography was addressed to quantify the lithium concentration over the state of charge (SOC) [9]. Strain-induced stress of a graphite anode was characterized with a micro-Raman mapping technique [10]. Changes in the mechanical properties of separators over life cycles have been investigated to determine their relationship with degradation in cell performance and capacity loss with simulations [11] and experiments [12]. Stress evolution in a silicon thin-film electrode was measured by using a multi-bean optical sensor technique [13]. A modal test was conducted to measure frequency responses of a single pouch cell over the SOC [14].

Thermal issues have been studied because the lifespan and states of LIBs are affected by temperature [15]. Advanced thermal management apparatuses were suggested to control operational temperature. These apparatuses include a liquid metal [16], a cold plate [17], a heat pipe [18], phase change materials [19], and composite phase change materials [20]. Thermal optimization was conducted for a LIB pack under extreme operational conditions [21]. Thermal abuse was simulated to

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Nomenclature

E_{neg}	modulus of elasticity of the negative electrode, GPa
E_{pos}	modulus of elasticity of the positive electrode, GPa
$i\delta_{SOC}$	uniform internal of SOC
k_{eq}	equivalent stiffness, Nm^{-1}
k_i	stiffness of the *i*th layer, Nm^{-1}
P_{neg}	porosity of the negative electrode
P_{pos}	porosity of the positive electrode
ΔSOC	interval of the SOC
SOC_0	fully discharged state
x_{Li}	Li concentration in the anode
$\mathbf{K}_i$	Stiffness matrix at several SOC, Nm^{-1}
$\mathbf{K}_i^{FEM}$	stiffness matrix of the full-order model of the component *i*, Nm^{-1}
$\mathbf{K}_i^{PROM}$	reduced-order stiffness matrix of the component *i*, Nm^{-1}
$\mathbf{K}_0^{PROM}$	reduced-order stiffness matrix at the fully discharged state, Nm^{-1}

elucidate effects of high temperature on capacity degradation [22]. Novel thermal management strategies [23] such as a lattice Boltzmann method [24] were also suggested. These studies generally used a 3-D finite element analysis to elucidate thermal behaviors of LIBs [24].

Multiple studies have been conducted to improve performance of battery management systems. These efforts can be classified into three categories: modeling, states estimation, and power management.

A variety of models, including a first order model with an integrator [25], a 1-D electrochemical model [26], an empirical dynamic voltage model [27], and a support vector machine based model [28] were proposed. An enhanced single particle model was suggested to consider temperature dependency when estimating the SOC [29]. A lumped thermal dynamic model [30], a coupled electro-thermal model [31], and a phenomenological multi-physics model [32] were also suggested for use in thermal management. A dynamic modeling procedure for real-time control of a LIB pack was proposed [33]. Performance and accuracy of these models were recently compared for application in electric vehicles (EVs) [34].

A Kalman filter [35], an adaptive Kalman filter [36], and a generic algorithm [37] were proposed with open-circuit voltage [38] and dynamic impedances [39] to estimate the SOC. Several methods including a neural network [40], an adaptive neuro-fuzzy [41], and an indirect non-intrusive method [42] were suggested with a single-point impedance [43] and on-board internal resistance estimation [44] to estimate the state of health (SOH). Recently, the error sources of online state estimation methods were investigated using error flow charts [45].

Several algorithms have been suggested for advanced power management. These efforts include an adaptive load compensator [46], demand response programming [47], convex programming [48], a Bayesian predictive modeling technique [49], efficiency maps [50], a hybrid approach [51], a cost-emission model [52], an equivalent consumption minimization strategy [53], a sliding model controller [54], and a sensorless quick charger [55]. Convex relaxations in the optimal control [56] and integrated optimization of battery sizing, charging, and power management [57] were also studied. A method for enhanced sample entropy-based health management was proposed for EVs [15].

Several studies addressed mechanical responses for characterizing dynamic states at the cell level [58]. Several phenomenological models have been proposed to predict the strain [59] and stress [60] of a cell. A modified stress model was suggested based on strain measurements by using a real-time optical acquisition system [61]. A coupled electrochemical, thermal, and mechanical model of LIBs was also suggested and validated with experiments [62]. These studies offer potential viability of mechanical measurements to develop a new generation of state estimation [63], health management [64], and power management [65] of battery management systems for EVs and hybrid electric vehicles (HEVs). However, Li-ion intercalation and phase transition [66] have not been considered in-depth in the pack level despite the fact that the periodic stresses caused by Li-ion intercalation and phase transition affect performance and degrade cells during operation.

To overcome these limitations, this study characterizes the dynamic responses and their evolution on the pack level for the first time with a high fidelity finite element model (FEM) and a parametric reduced-order model (PROM). The proposed modeling methods enable one to predict dynamic responses of a LIB pack and their evolution in a variety of deterministic and stochastic conditions. Specifically, the effects of evolution of mechanical properties of the electrodes on changes in dynamic responses are investigated. Studying dynamic responses and their evolution using a high fidelity model is difficult because of computational complexity. Heavy computational effort impedes a probabilistic analysis on the dynamic responses even though the fatigue life strongly depends on their vibration response. Deterministic analyses

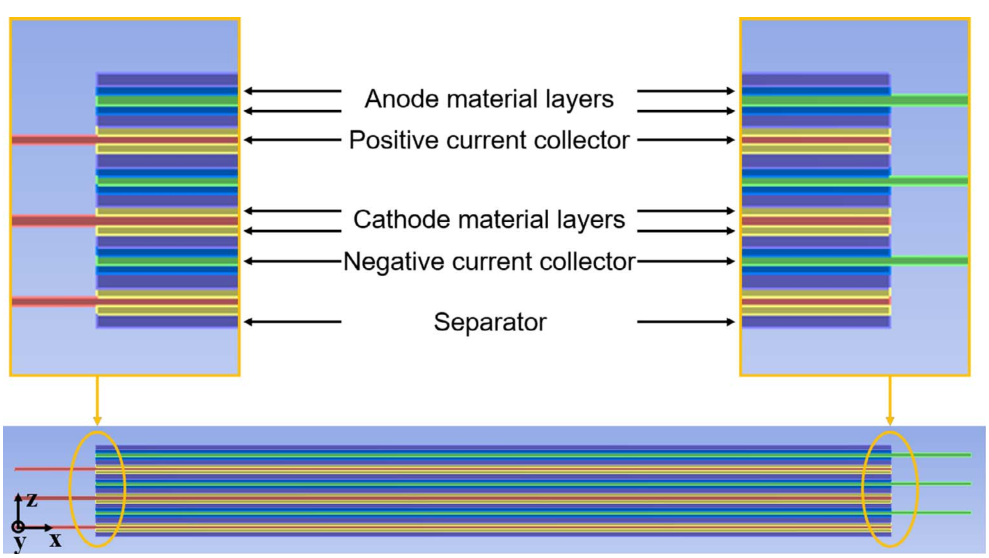

Fig. 1. Geometry of the jellyroll used in this study: the orange and green domains represent positive and negative current collectors, respectively. The yellow and blue domains represent the cathode and anode material layers coated on both sides of the current collector, respectively. The purple domain represents the separators located between the positive and the negative electrodes.