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Parametric reduced-order models of battery pack vibration including structural variation and prestress effects

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HIGHLIGHTS

- Effect of prestress and cell-to-cell parameter variations in HEV battery pack are investigated.
- Novel numerical methods are developed for the HEV battery pack having high modal density.
- Monte Carlo simulations are performed to examine the effects of cell-to-cell variations.

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ABSTRACT

The goal of this work is to develop a numerical model for the vibration of hybrid electric vehicle (HEV) battery packs to enable probabilistic forced response simulations for the effects of variations. There are two important types of variations that affect their structural response significantly: the prestress that is applied when joining the cells within a pack; and the small, random structural property discrepancies among the cells of a battery pack. The main contributions of this work are summarized as follows. In order to account for these two important variations, a new parametric reduced order model (PROM) formulation is derived by employing three key observations: (1) the stiffness matrix can be parameterized for different levels of prestress, (2) the mode shapes of a battery pack with cell-to-cell variation can be represented as a linear combination of the mode shapes of the nominal system, and (3) the frame holding each cell has vibratory motion. A numerical example of an academic battery pack with pouch cells is presented to demonstrate that the PROM captures the effects of both prestress and structural variation on battery packs. The PROM is validated numerically by comparing full-order finite element models (FEMs) of the same systems.

1. Introduction

Typical hybrid electric vehicle (HEV) battery packs are assembled by bolts or welds for joining cells within the pack and for integrating the battery structure into the rest of the vehicle. The prestress due to joining can affect the dynamic response of the structures significantly. In addition, HEV battery pack structures typically include dozens or even hundreds of cells. Because the cells are nominally identical, if the cells are arranged in a spatially repeating layout then the battery pack falls under the class of structures known as periodic structures. The dynamics of periodic structures are known to feature very high modal density in many frequency bands. The high modal density combined with small, random structural variations among the cells (which are unavoidable in practice) can lead to drastic consequences on the structural dynamics. In particular, they can exhibit Anderson localization [1–3], where the vibration energy is spatially confined to a small region of the structure.

The focus of this work is to develop computationally efficient methods for predicting the vibratory response of a battery pack that may suffer from localization. It is believed that certain battery packs, such as those with pouch cells, may be especially susceptible to localization phenomena. Localization can lead to battery cell damage due to sharp increases in local vibration amplitude and stress levels in a pack, which in turn can lead to mechanical or electromechanical failure.

Stress and failure issues in battery packs have been investigated in several previous studies. For example, Offer et al. [4] provided a new concept of module design and a fault diagnosis technique in

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electric vehicle batteries. They focused on testing the full battery pack and diagnosing subsequent problems related to cells to demonstrate how a full vehicle test can be used to identify malfunctioning strings of cells. Xiao et al. [5] developed a multi-scale approach for the stress analysis of polymeric separators in a lithium-ion battery. They presented a finite element method based on a multi-scale approach for the stress analysis of the separator in a battery cell. Sahraei et al. [6] revealed the underlying physics and identified important groups of parameters. To do that, they performed tests on pouched and bare lithium-ion cells under several loading conditions. They validated the test by numerical simulations. The outcomes from the test data were used for the development of an advanced constitutive model needed for strength/weight optimization and safety assessments of Li-ion batteries. Kenney et al. [7] established the relationship between cell-to-cell variations due to their manufacturing process and their overall impact on a full battery pack. They used mathematical modeling techniques to predict how slight variations in the manufacturing of electrodes manifest themselves in an operational battery module. The variation in the performance of the module has been quantified as a function of the manufacturing variation at the electrode level. Dubarry et al. [8] developed modeling and simulation techniques to show that accurate battery pack simulations can be achieved if cell-to-cell variations are taken into account. They used an accurate single-cell model which was validated against experimental data to provide high fidelity pack simulation.

However, the structural characteristics of the entire battery pack with very high modal density have not been previously explored. Therefore, the literature does not address the possible occurrence or prediction of localization in battery packs due to random structural variations among the cells.

In order to properly account for the effects of random variations, statistical dynamic response calculations are needed. Such statistical calculations are hard to perform using linear methods because the mode shapes of a pack depend in a nonlinear fashion on the parameters of each cell. The alternative is to use sample-based statistical analyses, such as Monte Carlo simulations. However, typical finite element models (FEMs) of battery packs have several million degrees of freedom (DOF). Thus, the computational time for obtaining just a single sample can be on the order of a day. This may make it infeasible to perform Monte Carlo simulations with FEMs.

To overcome this issue, in the field of structural dynamic analysis, component mode synthesis (CMS) [9–15] is well established as an alternative to conventional FEMs with large numbers of DOF. CMS belongs to a wide class of domain decomposition techniques. In a CMS approach, the global structure is divided into several substructures, and the DOF of each individual substructure are reduced significantly. Then, the substructures are reconnected, and the dynamic response of the system is predicted very efficiently and accurately. However, classical CMS must be modified in order to account for parametric variability in the structure. Thus, alternate, design-oriented techniques have been developed. One such approach is to generate what is referred to as parametric reduced-order models (PROMs). PROMs were introduced initially by Balmés et al. [16,17] to avoid the expensive process of reanalysis of complex structures. In addition, several other PROM methods have been developed [18–22].

In particular, the multiple-component PROMs (MC-PROMs) [21] have been developed by the authors. MC-PROMs are well suited for the structure modeled with shell-type finite elements. However, MC-PROMs have several drawbacks, namely: (1) a numerical instability of system level matrices can be encountered due to the transformation matrix, (2) MC-PROMs do not capture well elemental level nonlinearities for thickness variations of brick type finite elements, and (3) the interface DOF are hard to reduce. Thus, the next-generation PROMs (NX-PROMs) technique have been developed recently to overcome these drawbacks [22]. The concepts used in NX-PROMs are applied herein to capture the prestress variations.

The PROM techniques are highly efficient methods for estimating the statistics of the structural dynamic response. However, for a structure with very high modal density, previously developed PROMs have to be modified to efficiently capture the dynamic response. In particular, such a modification can be similar to the component mode mistuning (CMM) [23] method. CMM was developed for predicting the dynamic response of bladed disks found in turbo-machinery. Typically, these bladed disks suffer from high modal density. Thus, small structural variations in the blades significantly affect the system-level dynamic response. Nonetheless, it has been shown that the mode shapes of a mistuned bladed disk can be represented as a linear combination of the mode shapes of the tuned bladed disk [24]. This allows CMM to capture the dynamic response effectively with a small number of DOF, and that is the inspiration for the new PROMs introduced in this work.

This paper is organized as follows. In Section 2, structural properties and dynamic characteristics of HEV battery packs are evaluated. Next, in Section 3, PROM is applied for prestress variations, and new concept of PROM is developed for cell-to-cell structural variations. In Section 4, numerical examples of an academic battery pack models are used to demonstrate and test the proposed methods, including a Monte Carlo simulation technique that supports fatigue life prediction by quantifying stochastic effects in the forced response and sensitivities to various sources of parameter variation. Finally, conclusions are summarized in Section 5.

2. Structural properties and dynamic characteristics of battery packs

HEV battery packs typically have 100–300 individual cells that are nominally identical. To demonstrate the structural dynamic characteristics of a battery pack, a simplified academic model of a pack of pouch cells was developed using finite elements as shown in Fig. 1. The nodes on one end of the pack are totally fixed. The prestress and dynamic loads are applied to nodes on the other end of the structure. The prestress loads are applied to the longitudinal direction to compress the structure, and the harmonic excitations are applied to all three (x, y, z) directions. The excitation frequencies are in the range of 2200–2350 Hz. A total of 20 nominally identical cells are stacked. Typically, foam or epoxy stiffness layers can be placed between cells. These elements are nonlinear materials, but they are soft. Thus, herein these nonlinear materials are ignored.

To evaluate how the prestress variations in the structure affect the structural response, two different levels of prestress were applied: 150 kN and 470 kN. Fig. 2 shows the forced responses of the center node of the 1st cell for the different levels of prestress. The responses obtained by full-order models are significantly different for each level of prestress. For the prestress levels, the intent is to demonstrate that the PROMs can capture the structural dynamics for different prestress values that lead to a significant change in the forced response. The values 150 kN and 470 kN were chosen because they met these criteria for demonstrating the PROM performance. However, it should be noted that these are just two sampled prestress values, and the precise numbers do not have special significance.

Fig. 3 shows a single cell and the frames that join it to the adjacent cells. The single pouch cell is a plate-like structure for which the small, random structural variations are modeled by perturbations to the elastic modulus (E). The (nominally identical) cells are mechanically coupled through the frames, which induces a