Enhanced Hierarchical Multiscale Modeling for Off-Road Mobility Simulation with Neural Network Surrogate Model

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Abstract

Accurate prediction of off-road mobility capability is of paramount importance in making reliable go/no-go decisions in operational planning [1]. The development of high-fidelity off-road mobility simulation, however, poses critical challenges due to the computational complexity stemming from multiple scales involved in the granular terrain dynamics. Since terrain deformation, resulting from the physical interaction with tires on macro scale, is explained by complex granular particle motions occurring in the order of millimeters to micrometers [2], the tire-soil interaction problem is essentially viewed as a multiscale problem. In consideration of the nature of vehicle-terrain interaction problems, the hierarchical FE multiscale off-road mobility modeling approach was recently proposed as shown in Fig. 1(a) [3], and it has proven to be effective in predicting vehicle mobility on granular terrain [4]. Despite the massive parallel processing which can be utilized to compute stress responses from many DE RVEs [3], speedup of the lower-scale DE RVE calculation is required to enable quick prediction of off-road vehicle mobility performance. To address this issue, a neural network surrogate model is introduced to the hierarchical multiscale modeling of tire-soil interactions in this study.

As in well-established plasticity formulations for modeling path-dependent material failure behavior, the use of an incremental stress-strain relationship is a natural choice for developing a surrogate (data-driven) constitutive model exhibiting nonlinear material behavior [5]. Thus, the incremental stress and strain relationship of the lower-scale DE RVE is replicated at different states of the stress and strain by exploiting the learning capability of artificial neural networks for high-fidelity off-road mobility simulations.

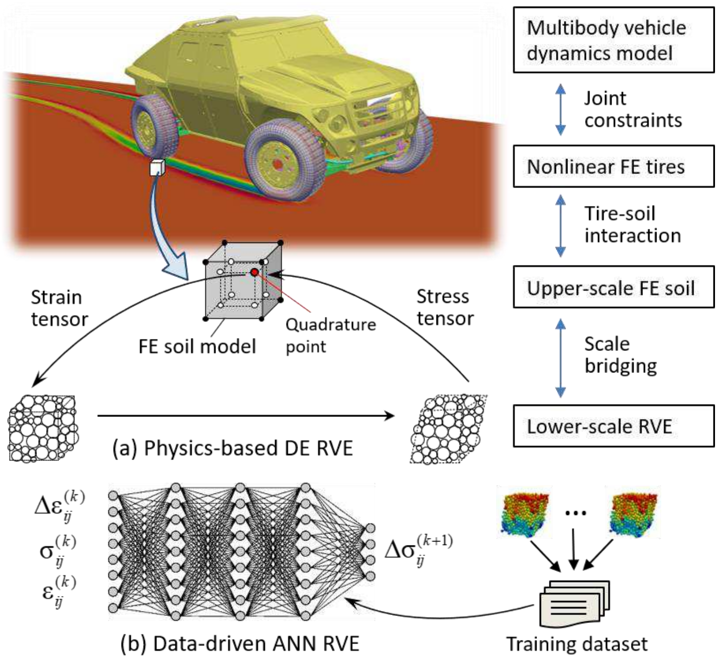

Figure 1: Multiscale off-rod mobility simulation framework

To this end, a neural network is constructed such that the incremental homogenized Cauchy stresses can be predicted given the incremental strain inputs as well as the current stresses and strains as shown in Fig. 1(b). By integrating the ANN surrogate RVEs into the multiscale computational framework as a lower-scale model, a new hierarchical FE-ANN multiscale terrain model is developed for high-fidelity off-road vehicle mobility simulations, as schematically shown in Fig. 1(b). With the ANN RVEs, the incremental Cauchy stress tensor, as well as the tangent moduli, can be obtained quickly in each time step. The ANN RVEs are developed using the open-source Keras library with TensorFlow [6].

To demonstrate the predictive ability of the FE-ANN multiscale terrain model in off-road mobility scenarios, a lane change maneuver simulation of a full-scale off-road vehicle model [4] is considered. Using a virtual single tire test rig simulation with the FE-DE multiscale terrain model, the DE RVE data are extracted from the soil patch to produce training data for the ANN RVE. To evaluate the tire-soil interaction behavior, the right-front and left-rear tire forces are presented in Fig. 2. Although training data are produced by the equivalent single tire test rig model only in a short cornering scenario, the right-front tire force behavior of the FE-ANN and FE-DE multiscale model agree well in the entire lane change maneuvering scenario. Furthermore, whereas the rear soil patch data are not used in training the ANN RVEs, the rear-left tire force behavior is also predicted well. It is worth noting that the computational time of the FE-ANN multiscale off-road mobility simulation was 27.2 hours, while that of the original FE-DE multiscale simulation was 140.5 hours. This resulted in a 71% reduction in computational time using the multiscale terrain model with the neural network surrogate model due to the fast processing in the lower-scale RVE computations. More details on the formulation, computer implementation, neural network training procedure, as well as the numerical results will be provided in the presentation at the conference.

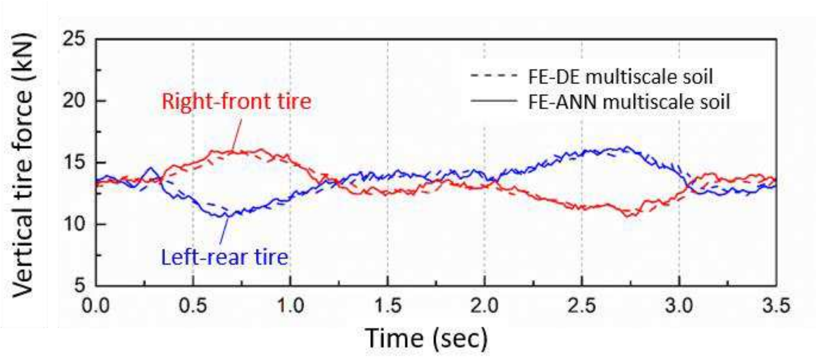

Figure 2: Vertical tire forces of lane change maneuver simulation using the FE-ANN multiscale terrain model. The results are in good agreement with those of the FE-DE multiscale model.

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