

Nonlinear Vibration Response Modeling and Performance Prediction of Air Suspension Using Machine Learning

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Model-Based Development (MBD) has become increasingly important in automotive development owing to the growing complexity of vehicle systems, including electrification, advanced safety technologies, and diversified customer requirements. By utilizing simulation models at the component, system, and vehicle levels throughout the development process, MBD can reduce development time and improve design efficiency. However, accurate vehicle performance prediction requires accurate component and system models. Constructing such models often requires extensive testing and parameter identification, especially for components exhibiting nonlinear behavior. As a result, significant development effort is still required even in MBD-based development processes. Air springs are typical examples of such components because their dynamic behavior is influenced by nonlinear spring, damping, viscoelastic, and friction characteristics. This study proposes a machine-learning-based approach for modeling nonlinear air suspension characteristics and predicting ride comfort.

The proposed method separates the nonlinear characteristics of an air spring into static and dynamic components. The static component mainly represents displacement-dependent force characteristics and can be obtained from conventional static tests routinely conducted during the development process. The dynamic component represents velocity-dependent behavior and includes nonlinear effects that often require complex mathematical modeling and parameter identification. By modeling these characteristics separately, the proposed approach leverages available engineering knowledge while applying machine learning only to the nonlinear behavior that is difficult to describe analytically. This framework enables efficient model construction while reducing the complexity associated with traditional physical modeling and parameter tuning.

To evaluate the proposed method, a nonlinear air spring model consisting of spring, damping, viscoelastic, and friction elements was employed. Simulation-generated time-series data were used for model training and validation. A recurrent neural network (RNN) was adopted because vibration response is strongly dependent on temporal information. The RNN consisted of one hidden layer with 50 units. Displacement and velocity were used as input variables, and force was used as the output variable. The mean squared error (MSE) was adopted as the loss function. The model was trained using excitation conditions generated by simulation and subsequently evaluated using vibration conditions that were not directly included in the training process.

Figure 1 illustrates the proposed modeling flow. The static and dynamic characteristics are modeled separately, and their outputs are combined to construct a ride comfort prediction model. Simulation results showed good agreement between predicted and reference responses under multiple excitation conditions. Under sinusoidal excitation conditions with amplitudes ranging from 5 to 20 mm and frequencies ranging from 1.5 to 5 Hz, the peak-to-peak force prediction error was approximately 5%. In addition, good prediction accuracy was maintained under different excitation frequencies and amplitudes. These results indicate that the proposed model successfully captures nonlinear vibration characteristics and can predict system responses under operating conditions that were not explicitly included in the training data. The prediction results reproduced both the amplitude and phase of the force response with good accuracy. This indicates that the proposed model can capture not only static nonlinearities but also dynamic effects associated with vibration behavior.

The results demonstrate that machine learning can effectively model nonlinear air spring characteristics while reducing dependence on complex physical modeling and parameter identification. The proposed approach has the potential to reduce model development effort and accelerate suspension performance prediction in the early design stage. Because conventional static test data can be directly utilized, model development effort may be reduced. These advantages suggest that the proposed framework can contribute to improving development efficiency while maintaining prediction accuracy. Future work will focus on validation using experimental bench-test data and extension of the proposed method to system-level ride comfort prediction.

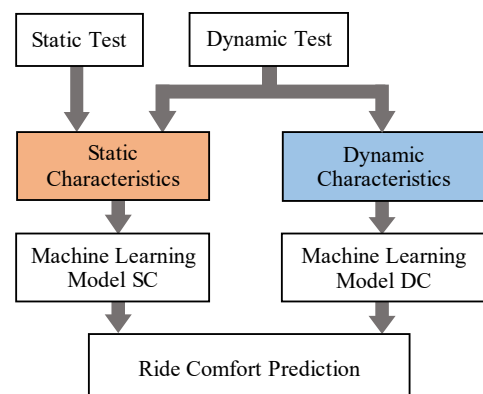


Fig.1 Proposed Modeling Method