Hybrid Modeling of Air Suspension for Chassis Module Force Transmissibility Prediction in NVH Analysis

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Abstract

Air suspension modeling is critical for estimating the NVH characteristics of chassis modules and full vehicles. However, accurate analytical modeling remains challenging because air suspensions exhibit inherently nonlinear behavior, and their force transmissibility varies with excitation amplitude. In previous research, a modeling technique was developed to predict the component-level behavior of an air suspension. Although the model showed reasonable agreement in component-level analysis, its predictive capability was limited when applied to chassis-level transmissibility prediction under varying loading conditions.

To address this limitation, this study proposes a hybrid modeling approach that incorporates component test results into an analytical model for chassis module analysis. By integrating experimentally identified characteristics into the model, the proposed approach more effectively captures the load-dependent force transmissibility of the air suspension than conventional analytical modeling alone. The developed model was applied to the prediction of chassis module transmissibility, and its validity was confirmed through correlation with experimental results. The results indicate that the proposed approach improves the agreement between predicted and measured NVH characteristics of chassis modules equipped with air suspension.

Keywords: *NVH, Air Spring, Hybrid modeling, Chassis module*

1. Introduction

Accurate prediction of the noise, vibration, and harshness (NVH) performance of a chassis module requires the development of reliable analytical models for key suspension components, such as coil struts and air spring. In particular, air spring exhibit strong nonlinear characteristics arising from the compressibility of the air spring, internal friction, and valve dynamics, which make accurate modeling more challenging compared to conventional components [1], [2].

Previous studies have identified that, under stick conditions, the force transmissibility of an air strut varies depending on the magnitude of the input load, and analytical models incorporating such nonlinear behavior have been proposed [3]. However, applying these models to practical product development requires precise knowledge of the input load acting on the air spring. In real vehicle operating conditions, the input load varies significantly depending on excitation paths and driving scenarios, making it difficult to define accurately.

Furthermore, conventional analytical approaches, which approximate the nonlinear behavior of air spring using linear models, inevitably introduce model uncertainty. As a result, discrepancies between simulation results and experimental measurements remain, limiting the reliability and applicability of such models.

To address these limitations, this study employs a blocked force–based measurement technique to more realistically characterize the input loads acting on the air spring [4], [5]. The measured blocked force is then used as the excitation input to obtain force transmissibility and FRF data, enabling an experimental characterization of the dynamic behavior of the air spring.

In addition, a hybrid modeling approach is proposed, in which the chassis module is represented by a FE model, while the air spring is modeled directly using experimentally obtained data [6], [7]. This approach allows the complex nonlinear characteristics of the air strut to be incorporated without excessive simplification, while improving the overall prediction accuracy of the system-level NVH response.

The proposed methodology overcomes the limitations of conventional purely analytical approaches and provides a practical and reliable framework for NVH prediction in vehicle development.

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2. Experimental Evaluation of Air Spring

2.1 Input Blocked Force for Air Spring

To identify the input Force acting on the air spring, a blocked force–based measurement approach was employed. The conceptual representation of the blocked force is illustrated in Figure 1 and Eq. (1). The air spring is mounted on the suspension lower arm, and in this study, the blocked force at the mounting interface with the lower arm was selected as the measurement target.
To this end, a dedicated adapter was designed and installed at the mounting interface, and a virtual point technique was applied to obtain the blocked force in 6-DOF [8]. A schematic of the measurement system is shown in Figure 2, and the measured blocked force is presented in Figure 3.
Based on the measured blocked force, the operational force acting on the air spring was subsequently estimated. The conceptual definition of the operational force is described in Eq. (2).
In order to estimate the operational force, the input point inertance (IPI) at the lower arm mounting location as well as the IPI at the air spring interface are also required [9]. In this study, these IPIs were obtained using a FE model.
The procedure for estimating the operational force using the blocked force and the corresponding IPIs is illustrated in Figure 4. The final estimated operational force applied to the air spring is presented in Figure 5.

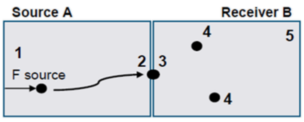

Figure 1. Blocked force diagram of the AB assembly

$$F_{bf2}^{A} = [H_{42}^{AB}]^{-1} \cdot a_4 \qquad (1)$$

$$F_{op3}^{B} = [H_{33}^{B} + H_{22}^{A}]^{-1} \cdot H_{22}^{A} \cdot F_{bf2}^{A} \qquad (1)$$

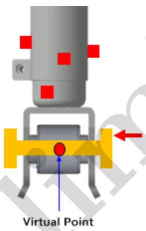

Figure 2. Measurement of the air spring input blocked force

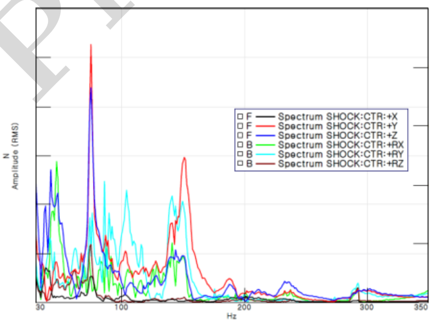

Figure 3. Air spring input blocked force results

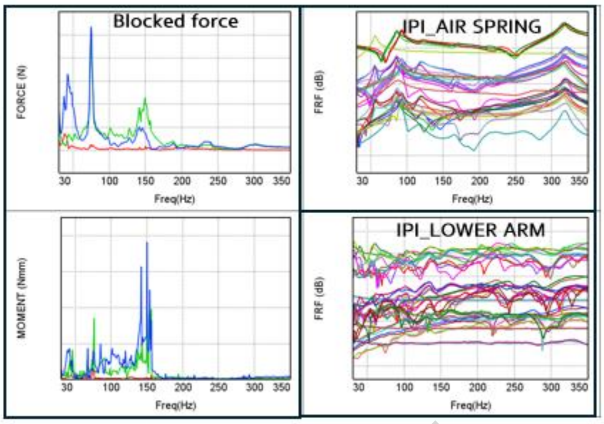

Figure 4. IPI (air spring, lower arm), Blocked force results

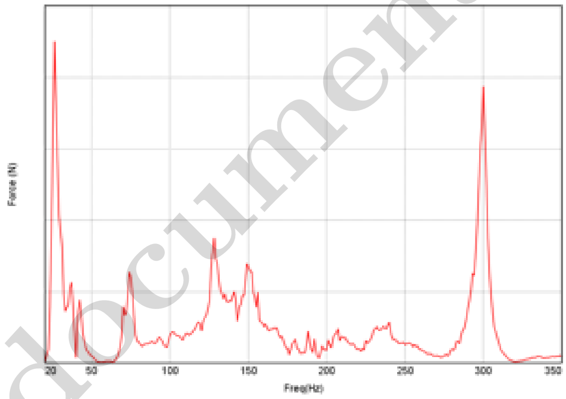

Figure 5. Result of air spring operation force

2.2 Dynamic Characteristics of Air Spring

The previously estimated operational force was applied as the input excitation to measure the force transmissibility of the air spring. In addition, a separate excitation with a constant amplitude of 30 N was applied up to 350 Hz under the same conditions, allowing the force transmissibility to be evaluated as a function of excitation magnitude. This enabled a comparative analysis of the force transmissibility characteristics with respect to input load levels.
All measurements were conducted under slip conditions. In actual vehicle operation, loads are transmitted through the air spring with relative displacement rather than under stick conditions [10]. Therefore, slip conditions were adopted to more realistically represent in-vehicle behavior. Furthermore, since current chassis module NVH evaluations are typically performed up to 350 Hz, the component-level test of the air spring was also carried out within the same frequency range (30–350 Hz).
Due to limitations in the maximum output force of the exciter, it was not feasible to directly apply the initially estimated operational force. Instead, the input load was adjusted to a feasible level and used for excitation. The resulting dynamic characteristics are presented in Figure 6.
Under slip conditions, the force transmissibility of the air spring showed similar trends across different input load magnitudes. A noticeable drop in response around 60 Hz and its harmonic components was observed, this is attributed to electrical noise.

Finally, the experimental results were integrated with the FE model of the chassis module to perform hybrid modeling.

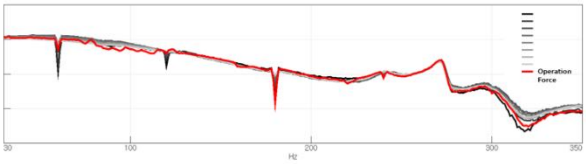

Figure 6. Air Spring Dynamic Characteristics for Different Input Load Levels (red: operation force)

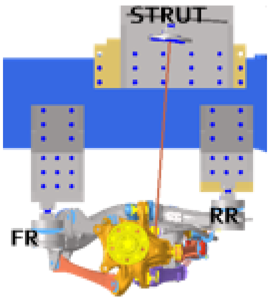

Figure 8. Chassis Module Mounting Point

3. Hybrid Modeling

Hybrid modeling was implemented using the FRFFLEX card in Nastran. The FRFFLEX approach allows the dynamic relationship between two nodes to be defined in terms of FRFs [11], [12].

During the dynamic characterization, not only the force transmissibility but also the FRFs were measured by attaching accelerometers. In addition, the IPI at both the input and output locations was simultaneously obtained. Based on these measured data, the FRFFLEX card was constructed, and a schematic representation of the overall model is shown in Figure 7.

To validate the hybrid modeling approach, the predicted force transmissibility (red) was compared with the corresponding experimental results (black). Furthermore, the results obtained using a fully FE model including air spring (blue) were also included for comparison, as presented in Figure 9.

The results show that the hybrid modeling approach based on experimental data improves the prediction accuracy of force transmissibility compared to the conventional FE-based air spring model. This improvement is particularly evident in the air spring region and is further confirmed by comparing the RMS values of the force transmissibility at the overall mount locations.

In this study, only 3-DOF were considered for the FRF and IPI representation. In addition, a non-correlated FE model was used for the chassis module, which resulted in some discrepancies between the prediction and experimental results. Nevertheless, it is expected that the prediction accuracy of force transmissibility can be further improved by extending the degrees of freedom in the FRF and IPI and by enhancing the correlation of the chassis FE model.

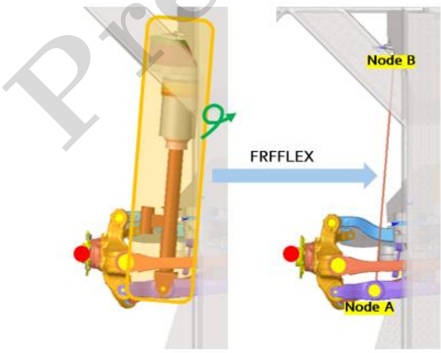

Figure 7. Air Spring Model Replaced with FRFFLEX

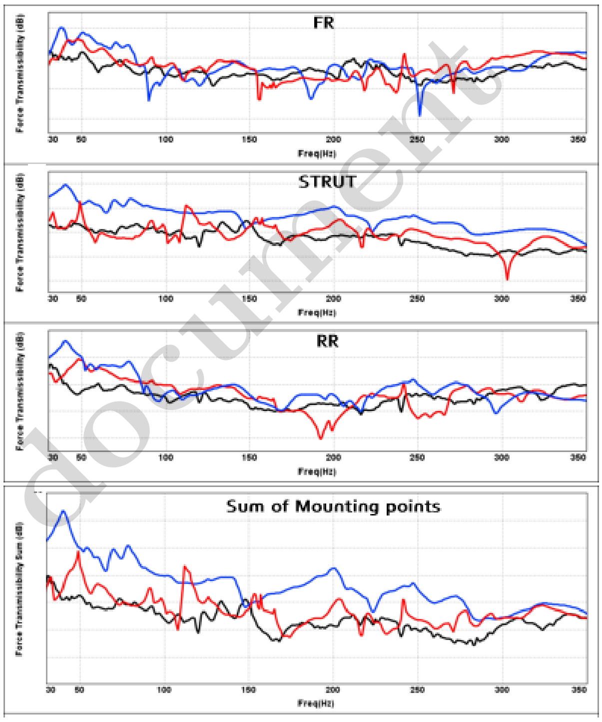

Figure 9. NVH Performance Prediction Results of the Chassis Module Using Hybrid Modeling (black: test, blue: full FE, red: hybrid modeling)

4. Conclusion

In this study, a blocked force–based input load estimation and hybrid modeling approach was proposed to address the limitations of conventional analytical models in capturing the nonlinear characteristics of air springs. The blocked force at the lower arm mounting interface was identified using a virtual point technique, and the corresponding operational force acting on the air spring was subsequently estimated. In addition, dynamic characteristics and force transmissibility were experimentally evaluated under slip conditions, enabling a more realistic representation of in-vehicle behavior.

A hybrid modeling approach was then developed using the FRFFLEX card in Nastran, where experimentally obtained data were incorporated into the model and combined with a FE model of the chassis module. The results demonstrate that the proposed hybrid modeling approach improves the prediction accuracy of force transmissibility compared to

the conventional FE-based air spring model. This improvement is particularly evident in the air spring region and is further supported by the comparison of RMS values across the overall mount locations, indicating that the test-based model better captures the actual system behavior.
However, in this study, only 3-DOF were considered for the FRF and IPI representations, and a non-correlated FE model was used for the chassis module. As a result, some discrepancies were observed between the predicted and experimental results in certain frequency ranges. Future work will focus on extending the degrees of freedom in the FRF and IPI representations and improving the correlation of the chassis FE model to further enhance prediction accuracy.
The proposed methodology provides a practical and effective approach for incorporating the complex nonlinear behavior of air springs into system-level analysis. It is expected to contribute to more reliable NVH prediction and improved performance assessment in vehicle development.

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