Development of an FBS Hybrid Model for Suspension Input Force Identification

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Abstract

To accurately predict vehicle NVH performance, subsystem-level validation should be conducted prior to full vehicle development. The Load Transfer Ratio (LTR) is widely used to evaluate force transmission characteristics of suspension systems. However, its reliability strongly depends on how the suspension input force is defined. This study focuses on the identification of suspension input forces for LTR evaluation, rather than direct LTR measurement. Conventional methods rely on dynamic force sensors, which inevitably include excitation system dynamics. To overcome this limitation, a Frequency-Based Substructuring (FBS) hybrid model is developed to identify wheel-center interface forces independently of actuator boundary conditions. Blocked forces at the excitation interface are obtained using an in-situ Transfer Path Analysis (TPA) method and combined with experimentally measured transfer functions through FBS synthesis to derive representative suspension input forces. To assess the influence of input force identification methods, the results are compared with forces obtained using a classical TPA approach. All forces are transformed to the wheel-center reference using Virtual Point Transformation (VPT) and represented as six-degree-of-freedom force vectors, enabling reliable LTR-based suspension NVH assessment.

Keywords: *in-situ transfer path analysis, virtual point transformation, blocked force, interface force, frequency-based substructuring*

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1. Introduction

Road noise is one of the key factors governing vehicle NVH performance, and its importance has increased further in electrified vehicles as powertrain-related noise decreases [1], [2]. Road noise can be defined as structure-borne noise generated by tire–road interaction and transmitted to the vehicle body through the suspension system. Accordingly, accurate prediction of this phenomenon requires quantitative evaluation of the input-to-output characteristics of the suspension system at the subsystem level.

Recently, chassis module test systems have been developed to evaluate NVH performance before full-vehicle testing [1], [3], [4].

Such systems enable independent assessment of the suspension transfer characteristics. The transmission behavior of suspension systems is typically evaluated by the load transfer ratio (LTR) or force transmissibility. However, the results are highly dependent on how the input force is defined, making reliable input-force identification essential.

Conventional measurements based on dynamic force sensors do not fully exclude the dynamic characteristics of the excitation system and boundary conditions and therefore may not represent the actual suspension interface force accurately.

To address this issue, this study applies a Frequency-Based Substructuring (FBS) hybrid model to identify suspension input forces [5]. Specifically, blocked forces are obtained at the input-side interface by means of in-situ Transfer Path Analysis (TPA) and are then combined with transfer functions to estimate interface operating forces with reduced sensitivity to boundary conditions.

To investigate the influence of input-force definition, the following cases were considered:

- Case 1 : FBS using a test FRF (H_{33}^{B})
- Case 2 : FBS using a simulation FRF (H_{33}^{B})
- Case 3 : Operating force from Classical TPA
- Case 4 : measured by the dynamic force sensor

All input forces were transformed into six-degree-of-freedom wheel-center forces using Virtual Point Transformation (VPT) and were compared on a common basis.

2. Theoretical Background

2.1 Frequency-Based Substructuring (FBS)

FBS is a method for coupling the dynamic characteristics of substructures in the frequency domain, based on the interface conditions of force equilibrium and compatibility [5].
In this study, the active side (wheel adaptor : A) is defined as the actuator system, while the passive side (knuckle : B) is defined as the suspension wheel center. The interface force between the two subsystems is expressed as follows:

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

The target response corresponding to the interface operating force identified by FBS can then be calculated as follows:

$$p_5 = H_{35}^{B} \cdot F_{op3}^{B} \tag{2}$$

The terms in Eq. (1) and (2) are defined as follows:

- H_{22}^{A} : Input FRF (Adaptor)
- H_{33}^{B} : Output FRF (Knuckle)
- F_{bf2}^{A} : Blocked Force at Wheel Center
- F_{op3}^{B} : Operating Force at Wheel Center
- H_{35}^{B} : Transfer Function to Target
- p_5 : Target (for Validation)

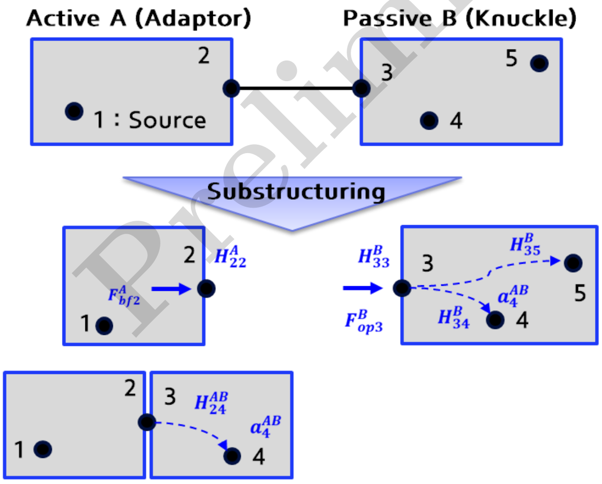


Figure 1. Schematic concept of substructuring.

2.2 Identification of input-side blocked force based on in-situ TPA

Blocked force is defined as the inherent excitation of the source with the influence of the passive side removed. In this study, an independent input force was identified at the actuator–adaptor interface by applying a matrix-inversion approach based on in-situ TPA. This force can be reused as long as the source-side structure remains unchanged. The relationship is given by Eq. (3).

$$F_{bf2}^{A} = [H_{24}^{AB}]^{-1} \cdot a_{4}^{AB} \tag{3}$$

2.3 Identification of input-side operating force based on Classical TPA

To estimate the force transmitted to the suspension wheel center, the matrix-inversion method of Classical TPA was applied. This approach directly back-calculates the input force from operational responses and transfer functions, and the resulting force was used as a reference for validating the FBS-based model. The corresponding relationship is given by Eq. (4).

$$F_{op3}^{B} = [H_{34}^{B}]^{-1} \cdot a_{4}^{AB} \tag{4}$$

2.4 Virtual Point Transformation (VPT)

All transfer functions and forces used in this study were expressed with respect to the wheel-center interface node. Because the experiment was carried out using multi-point measurements, Virtual Point Transformation (VPT) was applied to convert the measured data into six-degree-of-freedom forces and responses at the wheel center [6], [7]. By using VPT, interface forces and moments can be compared on a consistent basis, and experimentally measured transfer functions can be linked with simulation-based transfer functions within the same coordinate system.

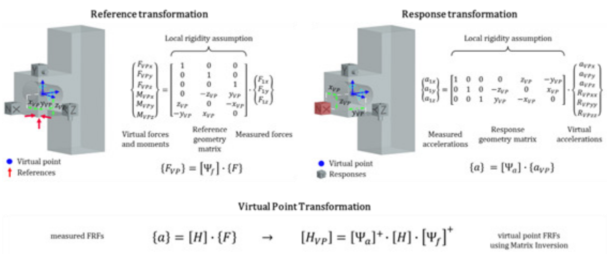


Figure 2. Definition of virtual point transformation.

3. Test System

3.1 Chassis Module Tester

A chassis-module-level NVH test rig was developed to reproduce actual vehicle operating conditions [1], [3], [4]. A newly developed large-capacity linear actuator with a 1-ton class load capability was applied so that static preload and dynamic excitation force could be controlled simultaneously. This

configuration enables testing under conditions close to real vehicle operation.
In order to determine the quantitative load transfer characteristics of the chassis module, it is essential to define an input force that reflects the inherent dynamic characteristics of the suspension system. Accordingly, this study compares the force currently measured by the dynamic force sensor mounted on the test actuator with the force actually transmitted to the suspension wheel center, using several identification approaches, in order to establish a more physically representative definition of suspension input force.

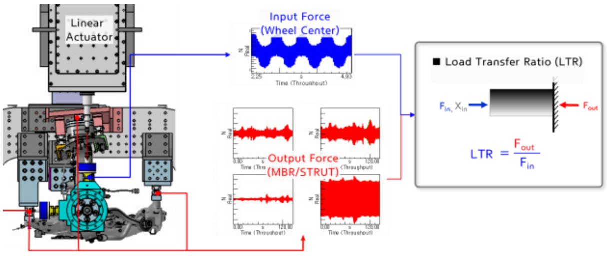


Figure 3. Linear actuator test system for chassis module

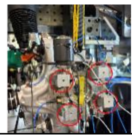
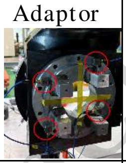
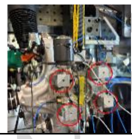
3.2 Measurement setup

A VPT-based measurement configuration was established in order to obtain the forces and transfer functions required for both TPA and FBS analyses. On the active side, an excitation block was installed to define a total of twelve excitation points. On the passive side, four tri-axial accelerometers were mounted to measure the response, and one additional accelerometer was installed at the target point for validation. The same configuration was applied symmetrically to the LH and RH sides of the chassis module, enabling the identification of 12-DOF interface forces.
Each measured quantity was assigned a specific set of excitation and response locations. H_{24}^{AB} was used as the transfer function for in-situ TPA, with excitation applied at the adaptor and the response measured at the knuckle. H_{34}^{B} and H_{35}^{B} were used as the transfer functions for Classical TPA, with excitation and measurement defined at the knuckle and target locations. H_{22}^{A} was used as the input-side transfer function for FBS, and H_{33}^{B} as the output-side transfer function for FBS.
The operational quantities a_4^{AB} and the validation response p5 were used as operational data during force identification and validation.

3.3 Operating Mode

To evaluate the dynamic characteristics of the chassis module, a sine-sweep excitation was applied in the vertical direction at the wheel center over the frequency range from 30 to 350 Hz. This excitation condition was selected to assess the mid-frequency response associated with road-noise-related behavior and to reproduce representative operational input characteristics.

Table 1. Sensor setup for the VPT-based measurements.

Measured quantity	Excitation point	Response point	Reference
H_{24}^{AB}	Adaptor 	Knuckle 	Transfer function for in-situ TPA
H_{34}^{B} (H_{35}^{B})	Knuckle 	Knuckle 	Transfer functions for Classical TPA
H_{22}^{A}	Adaptor 	Adaptor 	Input-side transfer function for FBS
H_{33}^{B}	Knuckle 	Knuckle 	Output-side transfer function for FBS
a_4^{AB} (p_5)	-	Knuckle 	Operating Data

3.4 Boundary Condition

All operational data and transfer functions were measured under a preload condition of 650 kgf, corresponding to the actual operating condition of the system. In particular, when the system was separated for transfer-function measurements, it was essential to reproduce the same preload as in the assembled operating condition. Therefore, a dedicated setup, as shown in Fig. 4, was implemented to realize this boundary condition. Through this approach, the transfer functions of the wheel adaptor and knuckle were obtained under conditions that were as close as possible to the actual operating state.

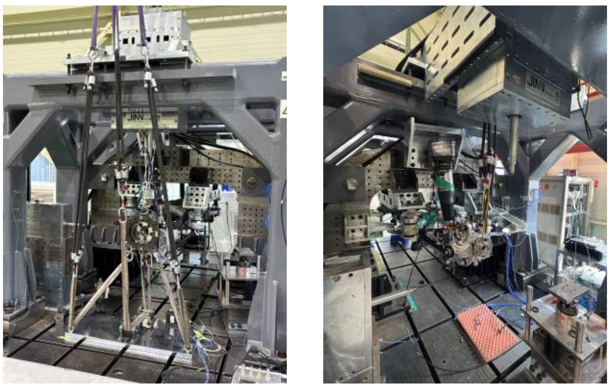


Figure 4. Pre-load implementation setup under separated conditions (left : H_{22}^{A}, right : H_{33}^{B}, H_{34}^{B}, H_{35}^{B})

4. Input Force Analysis

4.1 Operating force from classical TPA

An operating force based on Classical TPA was derived as a reference value for validating the FBS model. Classical TPA directly estimates the input force while reflecting the dynamic characteristics of the suspension system. In this study, the wheel-center transfer function and operational responses were used to calculate the operating force. The target response reconstructed from the identified force showed good agreement with the measured response, confirming that the result is sufficiently reliable to serve as a reference.

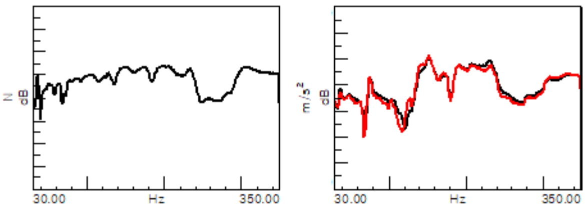


Figure 5. Operating force from Classical TPA (left) and validation at the target location (right: black – measured, red – TPA).

4.2 Operating force from FBS model

4.2.1 Blocked force from in-situ TPA

The blocked force used for FBS synthesis was extracted by means of the in-situ TPA method [2], [5]. When the target response was reconstructed using the blocked force obtained at the input-side interface, good agreement was observed at the target location. This confirms that the extracted blocked force represents a reliable description of the source excitation characteristics.

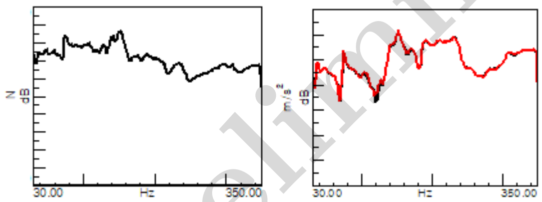


Figure 6. Blocked force identified by in-situ TPA (left) and validation at the target location (right: black – measured, red – TPA).

4.2.2 Transfer functions of active and passive sides

For FBS synthesis, the transfer functions of the active part (Adaptor: H_{22}^{A}) and passive part (Knuckle: H_{33}^{B}) were identified according to the measurement configuration defined in Table 1. By combining these transfer functions with the blocked force according to Eq. (1), the operating force based on the FBS model can be calculated.

In addition, an FBS hybrid model was constructed to investigate the feasibility of evaluating suspension characteristics prior to prototype manufacture. In this hybrid model, the reusable source-side characteristics namely the blocked force and the adaptor transfer function H_{22}^{A} were retained from the test model, while only the wheel-center transfer function H_{33}^{B} of the chassis module was replaced by a value obtained from the simulation model. This enabled an assessment of the potential of combining test and simulation models to predict suspension performance. Fig. 7 presents the difference between the test-based and simulation-based wheel-center transfer functions(H_{33}^{B}).

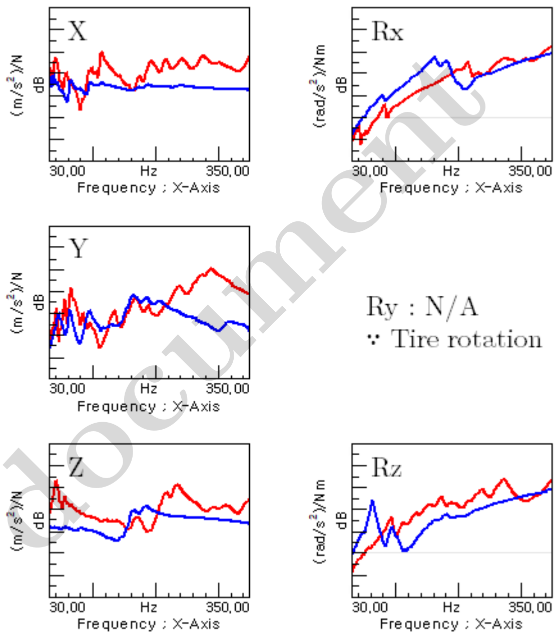


Figure 7. Difference between test-based and simulation-based wheel-center transfer functions of the suspension system

4.2.3 Comparison of Operating Forces

Fig. 8 compares the input forces obtained for each case under the chassis module test-rig excitation. Compared with the excitation-system force measured directly by the test rig (Case 4), the operating force identified at the suspension input while reflecting the actual suspension input characteristics (Case 1) was approximately 10 dB lower. This result indicates that the input force must be defined in a physically appropriate manner in order to estimate force transmissibility accurately.

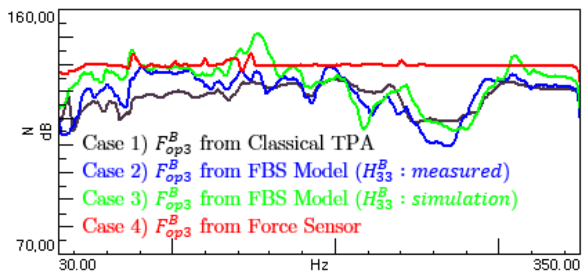


Figure 8. Comparison of operating forces for 4 cases.

When the FBS-synthesized operating force based on test data is compared with the operating force obtained from Classical TPA, the overall tendency is similar, but discrepancies appear in some frequency regions. This is due to the fact that the transfer functions used in the FBS model are measured under separated conditions, and in particular, the wheel-adaptor input transfer function cannot be measured under exactly the same boundary conditions as those during operation. In addition, the VPT approach models an actual surface-contact boundary as a point-contact interface, which can further increase the apparent error. To reduce these discrepancies, future work will investigate the application of FBS decoupling techniques.

Finally, when the passive-side transfer function was replaced by the simulation model in the FBS hybrid approach, the discrepancy increased further relative to the test-based result. This indicates that a higher level of correlation between the simulation model and test results is required before a simulation-based transfer function can be reliably used in a hybrid model. Nevertheless, the study also confirms the potential of using a flexible combination of test and simulation data to predict the performance of a target product.

5. Conclusion

In this study, suspension input-force definition methods were compared using a chassis module NVH test system, and an FBS-based hybrid methodology for input-force identification was proposed. Blocked forces identified by in-situ TPA were combined with transfer functions to derive interface operating forces, and the resulting forces were compared with those obtained from Classical TPA and from the dynamic force sensor installed on the test rig.

The results showed that the force measured directly at the actuator differs from the actual suspension input force by approximately 10 dB, demonstrating that the definition of input force directly affects force transmissibility. The FBS-based input force showed an overall trend comparable to that of Classical TPA, although some discrepancies can arise because of boundary-condition mismatch during transfer-function measurements and because of the point-contact assumption introduced by VPT.

Overall, suspension input-force definition is a key factor in subsystem-level NVH evaluation, and the FBS hybrid approach proposed in this study provides a practical means of deriving interface forces while reducing the influence of excitation-system dynamics. Further improvements are expected through refined boundary-condition implementation and the future application of FBS decoupling techniques.

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