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Modeling and Dynamics Study of Beam Leaf Spring System Based on Elastic Constraints

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Abstract: This paper introduces an innovative approach using elastic bushing constraints to simulate the practical limitations of leaf springs. A comprehensive rear suspension system is constructed for a specific vehicle, incorporating parameterized preload for the leaf springs to ensure alignment with the actual vehicle's forces and attitudes. Validation with real-world kinematics and compliance (K&C) dynamics data confirms the model's accuracy in representing vertical, longitudinal, and lateral stiffness, along with dynamic characteristics. The study demonstrates that the dynamic model of the multi-leaf plate spring suspension, grounded in bushing constraints for the beam accurately simulates the actual vehicle. The model exhibits flexibility and motion characteristics that closely resemble the real vehicle, demonstrating high accuracy and good computational convergence.

Keywords: Bushing constraint; Leaf spring; Dynamic model; K&C analysis

1. Introduction

Leaf springs are commonly used in the rear axle of micro-cars, pickup trucks, and the front and rear axles of trucks, and the accurate modeling and simulation technology of its dynamic model has been difficult [1,2]. The traditional Society of Automotive Engineers (SAE) three-link theory leaf spring modeling is simple and computationally efficient, but its parameters need to be obtained by mechanical property identification, and it is difficult to achieve a realistic simulation of the motion and deformation characteristics of the leaf spring [3,4]. The model, relying on a flexible body, is quite complex with numerous degrees of freedom, leading to extended computation times. It is generally avoided, especially in whole-vehicle simulations involving multi-plate spring contact friction [5,6], due to its resource-intensive nature. The discrete beam method is recognized as a method with higher accuracy for establishing the dynamics model of a multi-body system of leaf springs [6].

This paper utilizes the Beam method to establish a dynamic model for the rear leaf spring suspension of a specific vehicle. An innovative approach is introduced, incorporating bushing contact to simulate clamping constraints among leaf spring groups and frictional forces between individual leaf springs. The contact between the main and auxiliary leaf springs is defined using a contact function. Finally, force elements are applied to impose preload on the leaf springs, simulating precompression. The preload is parameterized for adjustability, enabling a close approximation to real-world vehicle dynamics. After the model is established, the K&C data of the real vehicle are used to verify the vertical, longitudinal, and lateral stiffness as well as the kinematic characteristics of the leaf spring suspension model.

2. Main parameters of the suspension system

2.1. Static deflection

“fc” in suspension static deflection is the ratio of suspension load Fω to suspension stiffness, c, when the vehicle is fully loaded, i.e., fc = Fω/c.

2.2. Inherent frequency

The intrinsic frequency of the vibration system composed of automobile front and rear suspension and its mass on the spring. The automobile front and rear body of the intrinsic frequency is represented by n_1 and n_2 (also known as partial frequency) and can be expressed in the following formula:

$$\begin{cases} n_1 = \frac{1}{2\pi}\sqrt{\frac{c_1}{m_1}} \\ n_2 = \frac{1}{2\pi}\sqrt{\frac{c_2}{m_2}} \end{cases} \tag{1}$$

where c_1 and c_2 are the stiffness of the front and rear suspensions (N/cm); m_1 and m_2 are the on-spring mass of the front and rear suspensions (kg).

2.3. Dynamic deflection

The dynamic deflection of the suspension (f_d) is the vertical displacement of the center of the wheel relative to the frame from the fully loaded static equilibrium position to the limit of the suspension jump.

2.4. Four-wheel alignment parameters

Four-wheel alignment is designed to ensure that the vehicle travels in a straight line. For the design of the steering wheel of this car, several angles are considered, such as the kingpin inclination, kingpin offset, camber angle, and toe angle, collectively referred to as the four-wheel alignment parameters.

2.5. K&C parameters

The K parameter (Kinematics) refers to the suspension’s kinematic properties, while the C parameter (Compliance) pertains to the elastic kinematic properties of the suspension. Together, they are collectively known as kinematics & compliance, abbreviated as K&C parameters. Using the ADAMS/Car module, the geometric model of the system is parameterized. Based on the principles of multibody system dynamics and employing the Euler-Lagrange equations, the analytical forces and motions of the system are calculated. Simulation analyses are then conducted for various suspension conditions, including K parameter scenarios such as parallel wheel hop and body roll, as well as C parameter scenarios like same-direction rebound torque loading, opposite-direction rebound torque loading, same-direction lateral force loading, opposite-direction lateral force loading, and braking force loading. The simulation results provide data for each condition in the suspension system. The accuracy of the modeling can be verified by comparing the analysis results.

3. Leaf spring modeling

3.1. ADAMS modeling preparation

The chassis parameters required for modeling are extracted: the attribute parameters of the spring, damper, limit block, bushing, etc., are extracted and input into the ADAMS file for calling in the modeling.

The topology of the chassis subsystems is the theoretical basis of dynamic analysis, before establishing the model, we first need to analyze the physical structure of the suspension system, reasonably simplify the relationship between the various components, and carry out chassis structure topology analysis. The main content includes checking the completeness of components, examining their interconnections, conducting a freedom analysis of the suspension system, and determining whether components need to be modeled as flexible bodies.

There are several rules to be followed in examining the interconnections.

(1) A mechanism member is connected to two mechanism members with a kinematic vice and a bushing respectively, and the bushing is equivalent to a spherical hinge.

(2) A mechanism component is connected to two other components using two bushings. One bushing is equivalent to a spherical joint, and the other bushing is equivalent to a Hooke joint.;

(3) A mechanism component is connected to another component using two bushings. Both bushings are equivalent to revolute joints with axes passing through the centers of the two bushings, enabling rotational motion.

(4) If there is a local degree of freedom between the parts of the mechanism, it is necessary to remove the local degree of freedom, such as replacing the spherical joint with a Hooke joint.

The process of ADAMS/Car modeling is carried out in a bottom-up manner. Specifically, a template is first established, followed by the creation of subsystems, and ultimately, the assembly of these subsystems into the desired system, adhering to the modeling sequence of template → subsystem → assembly.

The modeling process starts by checking for an existing template with a similar topology in the shared database. If found, it can be directly used or modified for efficiency. If no similar template exists, a subsystem template for the desired topology needs to be created.

The creation of a new template begins with the creation of a hardpoint, followed by the creation of the required components, as well as setting up the topological connection between the components, and the creation of force elements such as springs and dampers. Additionally, it is essential to establish input and output connectors between the suspension and other subsystems, allowing the assembly to be connected correctly.

After the suspension template is created, a subsystem is built on top of the template, in which the hardpoint positions and the characteristic files of the springs, dampers, and bushings in the model can be arbitrarily modified, facilitating suspension tuning analysis. In order to perform suspension analysis, it is necessary to apply excitation. In ADAMS/Car, there is a simulation and analysis test bench specially designed for suspension, which can perform all kinds of simulations related to automobiles, such as wheel hop, body roll, lateral force, and other tests. The subsystem is then assembled with the MDI_SUSPENSION_TESTRIG, and simulation parameters for input and output calculations are configured in post-processing.

The model is established based on the design load state, so all relevant parameters correspond to the design state. After assembling the suspension, it is necessary to calibrate it according to the design state to ensure that the model's behavior under design loads aligns with the actual vehicle forces. Additionally, parameters such as tire toe and camber need to be set to their design state values. With these adjustments, the assembled suspension system is ready for simulation calculations. The ADAMS model primarily consists of hardpoints, components, joints, and connectors, along with other auxiliary elements like geometry shapes and structural frames.

3.2. Analysis of leaf spring characteristics

The overall structure of the rear suspension with a leaf spring bridge is simple, but the modeling of the multi-leaf spring in it is complicated. To establish the leaf spring model, it is necessary to first analyze the structural characteristics of the leaf spring. Secondly, it is necessary to determine the leaf spring load state. Lastly, the geometric hardpoints of the leaf spring are obtained, including the center arc point of the leaf spring. The suspension model to be established in this paper represents an unloaded state. The leaf spring consists of five plates, with the upper three forming the main spring and the lower two forming the auxiliary spring. The entire leaf spring assembly is fixed on the axle using U-shaped bolts, as shown in **Figure 1**. The simplified constraints of the leaf spring set are shown in **Figure 2**. In addition to the constraints, there is also friction between the leaf spring plates and the plates during the deformation of the actual leaf spring.

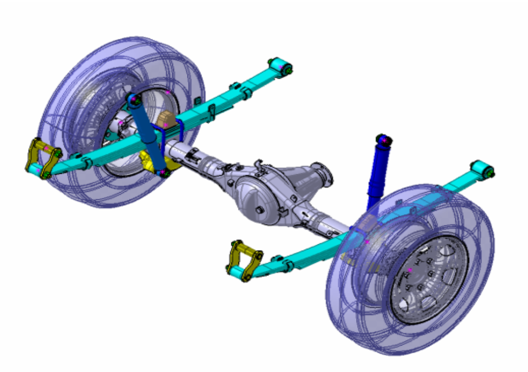


Figure 1. Multi-leaf steel plate spring rear suspension

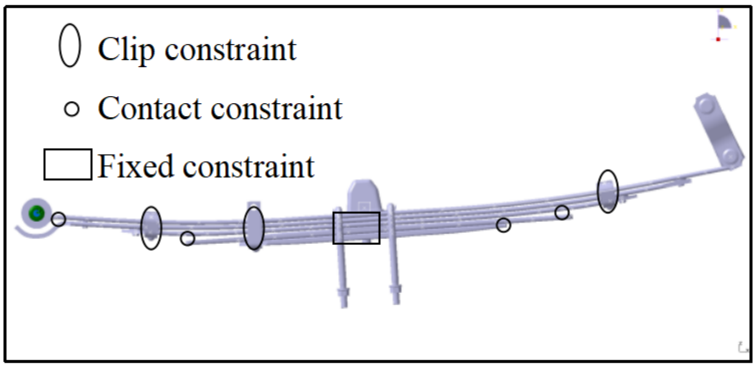


Figure 2. Simplified constraints for a leaf spring set

3.3. Establishment of leaf spring structure model

The steel plate is discretized to establish segmented beam elements. In theory, a higher number of discrete points leads to greater precision, but it also increases computational load. After the discrete beam unit is established, it needs to be connected with a massless beam unit. Therefore, it is essential to strike a balance in the discretization process for the leaf spring. The stiffness and damping characteristics of the beam unit are automatically calculated by the ADAMS software according to the cross-section shape and material properties of the leaf spring.

3.4. Leaf spring constraint setting

The constraint of the multi-leaf steel plate spring is crucial, and this paper utilizes bushings to simulate clamping constraints, friction between the leaf segments, and end-to-end contact of the leaf spring. The contact constraint form is maintained between the main and auxiliary plates of the leaf spring. The completed leaf spring model is illustrated in **Figure 3**. Adjusting the bushing stiffness for various positions can achieve the desired effects, such as simulating friction. For instance, allowing separation at the unclamped end of the leaf spring and imposing overall constraints at clamping locations.

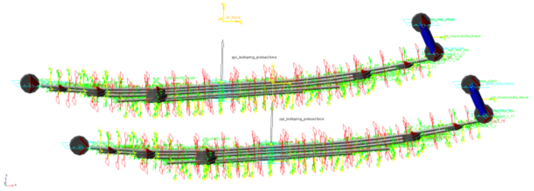
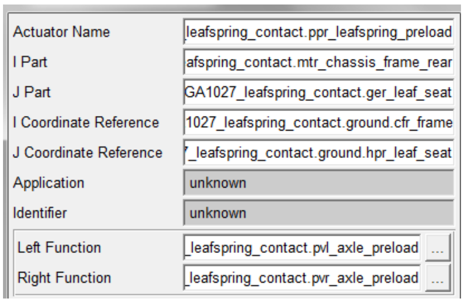


Figure 3. ADAMS/car model of leaf spring

3.5. Leaf spring preloading

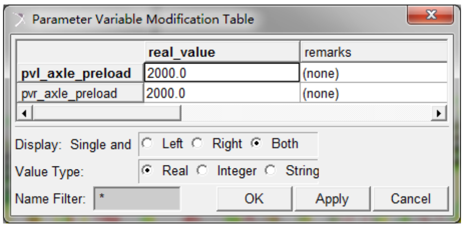
As the established leaf spring is not in a free state but assumes a specific geometric shape under certain loads, pre-loading is necessary. This ensures that the rear suspension model aligns with the design loads of the actual vehicle, achieving similar force and attitude conditions.



Actuator Name	leafspring_contact.ppr_leafspring_preload
I Part	afspring_contact.mtr_chassis_frame_rear
J Part	GA1027_leafspring_contact.ger_leaf_seat
I Coordinate Reference	1027_leafspring_contact.ground.cfr_frame
J Coordinate Reference	7_leafspring_contact.ground.hpr_leaf_seat
Application	unknown
Identifier	unknown
Left Function	_leafspring_contact.pvl_axle_preload
Right Function	_leafspring_contact.pvr_axle_preload

Figure 4. Creation of plate spring preload force unit

A force unit is added above the leaf spring perch, as shown in **Figure 4**, where the force is transmitted from the subframe or body to the leaf spring perch (axle) in the vertical direction. The magnitude of the force is parameterized so that it can be adjusted in the assembly model, as shown in **Figure 5**.



Parameter Variable Modification Table

	real_value	remarks
pvl_axle_preload	2000.0	(none)
pvr_axle_preload	2000.0	(none)

Display: Single and ○ Left ○ Right ● Both

Value Type: ● Real ○ Integer ○ String

Name Filter: *

Figure 5. Leaf spring preload parameterization interface

3.6. Leaf spring parameter setting

After the leaf spring is established, the rear suspension model is assembled, as shown in **Figure 6**. At this point, the suspension topology is finalized and additional parameters, such as overall vehicle details, bushing properties, and preload, are then set.

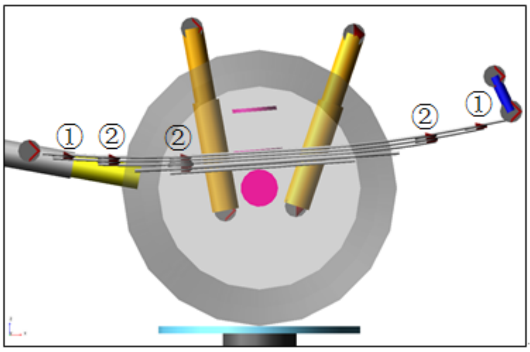


Figure 6. Multi-leaf steel plate spring rear suspension model

As shown in **Figure 6**, in the contact area of the ends of the 1st and 2nd leaf springs of the main spring, bushing ① is used to simulate the contact of the leaf springs. At the same time, bushing ① is set with a stiffness in the Z direction, allowing the leaf spring to detach when the wheel undergoes upward motion, and it exhibits dry friction during the leaf spring deformation. Bushing ② is used to simulate the clamp constraint and dry friction, and its properties are shown in **Figure 7**. The dry friction between the plates is related to the amount of deformation of the leaf spring; the greater the deformation, the greater the friction. In the suspension characteristics, this is manifested as suspension stiffness rather than damping characteristics [7].

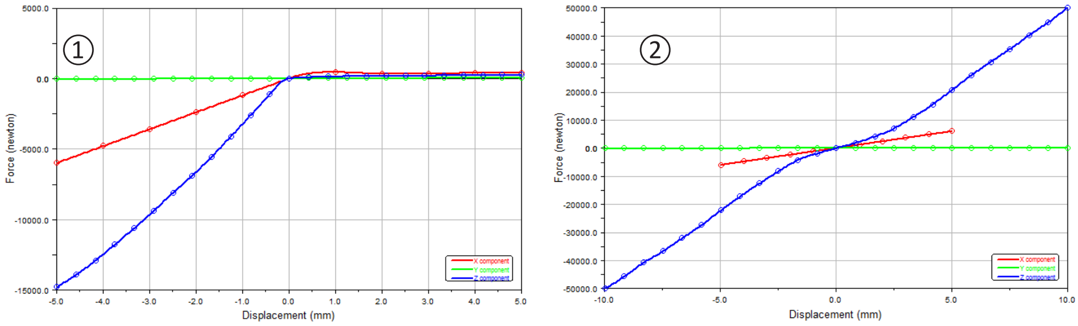


Figure 7. Stiffness characteristics of bushing ① and ②

Bushing ①: X-direction nonlinear stiffness simulates the friction in the compression section of the leaf spring, and the friction disappears in the relaxation section; Z-direction nonlinear stiffness simulates the contact in the compression section of the leaf spring, and the detachment of the leaf spring end in the relaxation section.

Bushing ②: X-direction simulates the friction between leaf springs, Z-direction nonlinearly simulates the clamp constraint, and the stiffness is small within the deformation ± 2 mm to simulate the clamp gap.

The bushing stiffness can be adjusted according to the results of the K&C test to ensure that it matches the test values.

4. Verification of leaf spring model

4.1. Validation of contact force between main and auxiliary springs of leaf springs

As shown in **Figure 8**, during the compression phase of the leaf spring assembly, contact forces arise between the main and auxiliary springs, and also between the two plates of the auxiliary spring. These contact forces act along the normal direction of the leaf spring contact surface, aligning with reality.

In the relaxation stage of the leaf spring, the contact force disappears and the ends of the main and auxiliary springs are separated, which is consistent with reality.

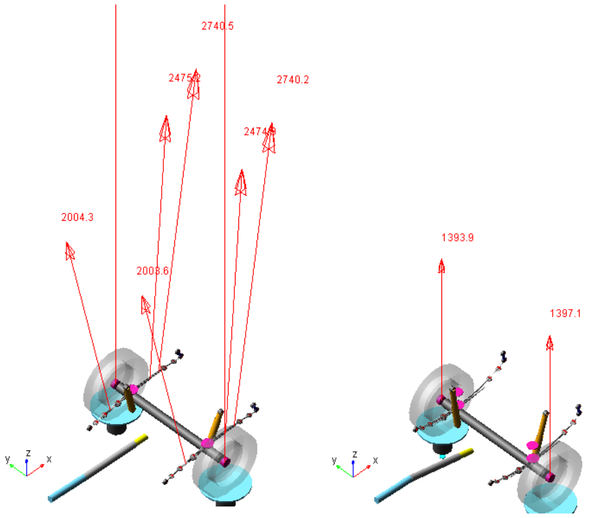


Figure 8. Schematic diagram of leaf spring contact force

4.2. Leaf spring end contact and disengagement verification

As shown in Figure 9, when the suspension reaches its upper rebound limit, contact occurs between the individual leaf springs. The bushing constraint between the main spring leaves effectively simulates leaf spring contact, preventing the lower leaf spring from passing through the upper leaf spring. The contact constraints allow for direct observation of the force distribution in the contact zones between the main and auxiliary leaves.

At the suspension's lower rebound limit, the area of contact between the leaves of the main spring, constrained by bushings, undergoes detachment. In the bushing-constrained clamping area of the leaf spring, the individual leaves remain engaged. The contact zone between the main and auxiliary leaves achieves detachment, effectively simulating the real-life deformation of the leaf spring.

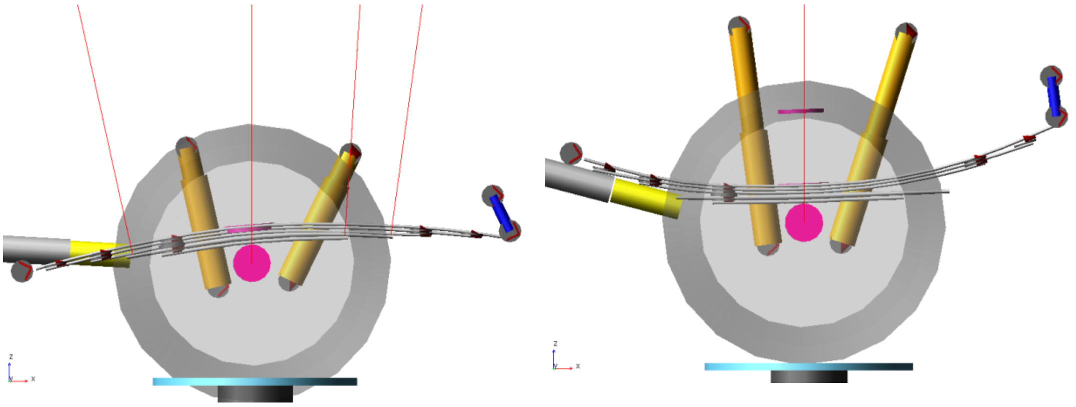


Figure 9. Schematic diagram of contact and disengagement of leaf spring ends

4.3. Suspension flexibility and deformation verification

The rear suspension is an integral bridge leaf spring suspension. In theory, parameters such as parallel wheel hop, camber, and wheelbase should not change. Therefore, comparing these aspects with experiments may not be significant. The key lies in comparing and validating the vertical stiffness (**Figure 10**), longitudinal displacement of the wheel center (**Figure 11**), longitudinal flexibility (**Figure 12**), and lateral flexibility of the suspension (**Figure 13**) with the actual vehicle.

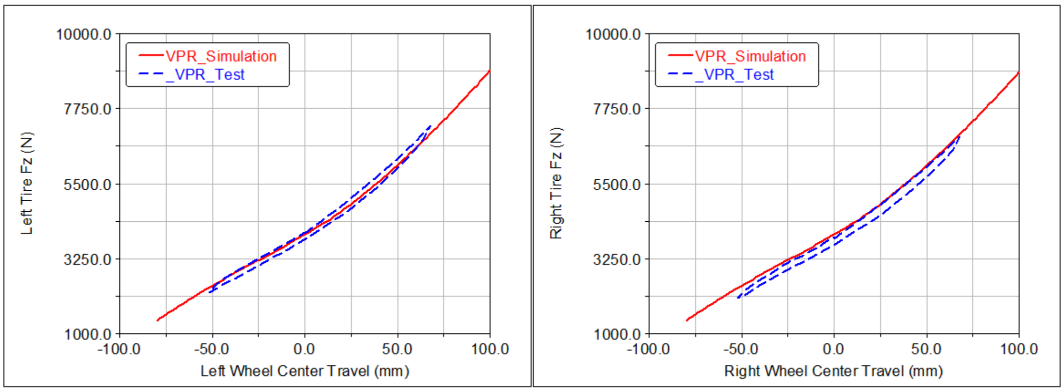


Figure 10. Verification of suspension stiffness

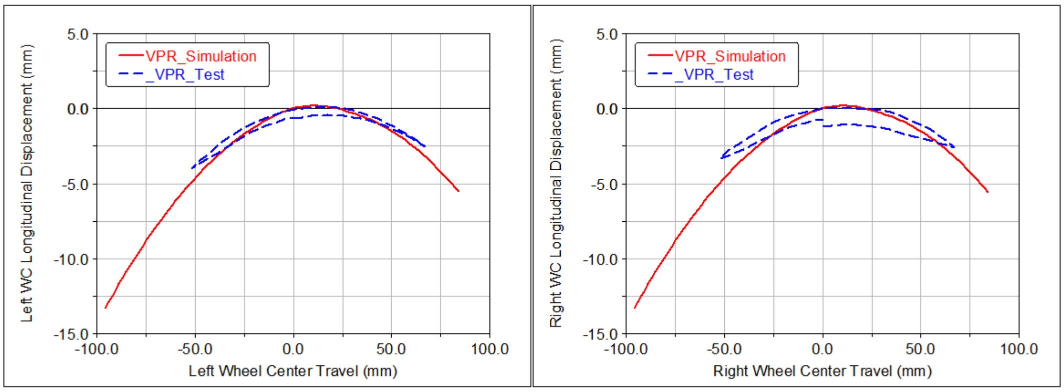


Figure 11. Verification of longitudinal displacement of wheel center

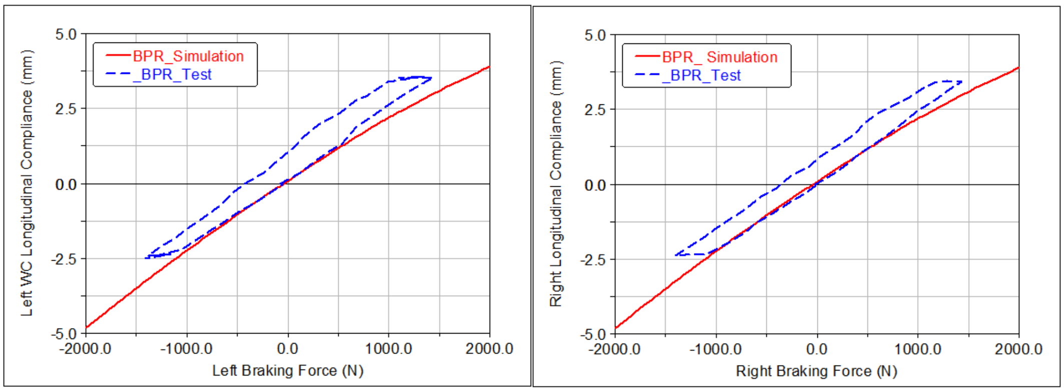


Figure 12. Verification of suspension longitudinal flexibility

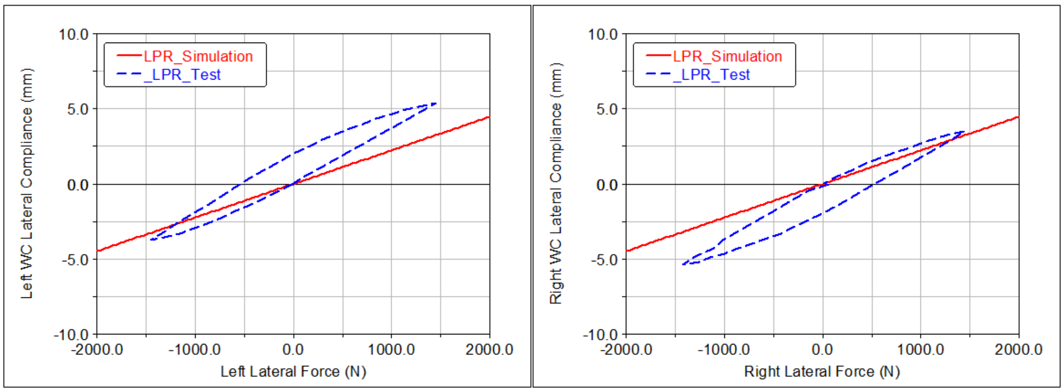


Figure 13. Verification of lateral flexibility of the suspension

Based on the above K&C characteristics verification results, the simulated suspension stiffness is in perfect agreement with the actual vehicle. This includes excellent matching of the contact positions between the main and auxiliary leaves and the suspension stiffness before and after the engagement of the auxiliary leaf. The correlation between the suspension wheel center's longitudinal displacement and wheel hop is remarkably high, indicating that the established model accurately represents the longitudinal deformation of the leaf spring, exhibiting high precision. The alignment of the lateral and longitudinal flexibility of the suspension with the experimental results from the actual vehicle is also very high, demonstrating that the simulation accuracy of the lateral and longitudinal stiffness of the steel plate spring is excellent and consistent with the real vehicle.

5. Conclusion

The method proposed in this paper for establishing the leaf spring rear suspension model with parameterized preload is adjustable, featuring a clear modeling approach and a relatively straightforward process. The suspension's vertical, longitudinal, and lateral flexibilities, as well as the compression deformation of the leaf spring, show a high degree of agreement with the results from actual vehicle experiments. The research indicates that the multi-leaf spring modeling method based on bushing constraints for the beam effectively approximates real vehicles. It demonstrates high simulation accuracy, fast computational speed, and good convergence, making it practically significant for the dynamic modeling and simulation of leaf spring suspensions.

Disclosure statement

The authors declare no conflict of interest.

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