



MODELING AND VALIDATION OF TRUCK SUSPENSION SYSTEMS USING ADAMS SOFTWARE

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ABSTRACT: This paper presents the modeling and validation of front and rear suspension systems in (4x4) trucks utilizing ADAMS software, focusing on leaf spring mechanisms essential for supporting light, medium, and heavy loads. The validation process compares the vertical stiffness of the multi-leaf spring in the front suspension and the dual-rate helper in the rear suspension which consists of main and auxiliary taper-type leaf springs. The stiffness values obtained from ADAMS simulations using the 'Parallel Wheel Travel' test are compared against those calculated analytically via beam theory and with reference values provided in engineering drawings. The comparative analysis indicates that the errors are within an acceptable range. Therefore, it is concluded that the suspension models are validated and can be used for full truck simulation.

KEY WORDS: *Leaf spring, ADAMS, Vertical stiffness, Truck, Beam theory*

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MODELIRANJE I VALIDACIJA SISTEMA VEŠANJA KAMIONA KORIŠĆENJEM ADAMS SOFTVERA

REZIME: Ovaj rad predstavlja modeliranje i validaciju sistema prednjeg i zadnjeg vešanja u kamionima (4x4) korišćenjem ADAMS softvera, fokusirajući se na mehanizme lisnatih opruga neophodnih za podupiranje lakih, srednjih i teških tereta. Proces validacije upoređuje vertikalnu krutost višelisnate opruge u prednjem vešanju i dvostruke pomoćne opruge u zadnjem vešanju, koja se sastoji od glavnih i pomoćnih lisnatih opruga konusnog tipa. Vrednosti krutosti dobijene iz ADAMS simulacija korišćenjem testa „Paralelni tok točka“ upoređuju se sa onima izračunatim analitički pomoću teorije grede i sa referentnim vrednostima datim u inženjerskim crtežima. Uporedna analiza pokazuje da su greške u prihvatljivom opsegu. Stoga se zaključuje da su modeli vešanja validirani i da se mogu koristiti za kompletnu simulaciju kamiona.

KLJUČNE REČI: *Lisnata opruga, ADAMS, vertikalna krutost, kamion, teorija grede*

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INTRODUCTION

In the automotive sector, different types of springs are intended to absorb mechanical shocks and ensure good comfort for passengers. Among these are the leaf springs, widely used in utility vehicles, vans, and trucks and meant to support medium and large loads without compromising vehicle performance.

For many years, leaf springs have been used in vehicles, particularly commercial vehicles, due to their robustness, reliability, and cost-effectiveness [4], which are generally used in different positions within vehicles: in the rear axles of utility vehicles and vans or in the front and rear axles of trucks and trailers.

The leaf springs have sufficient rigidity to support the car body and transmit the load from the chassis to the axle. At the same time, long leaf springs can also contribute to maintaining longitudinal stability [8].

The leaf spring comprises several elements that interact with each other, making its structure complex compared to the other elastic elements [9]. The longest leaf at the top of the spring is known as the master leaf. It is curved at both ends to form spring eyes. The center bolt is the critical part located in the center of the leaf springs. Its task is to bring together all the leaves. Additionally, the U-bolt provides the necessary force to securely fasten the leaf spring and its associated components. The shackle ensures the connection between the leaf spring and the chassis, it can be located at the front or rear of the leaf spring. Rubber bushes offer a cushioning effect for the leaf springs, with steel enclosures for the front ones and an entirely rubber composition for the rear ones. Rebound clips maintain leaf spring alignment and prevent lateral movement while the vehicle is in motion. The bump stop is usually made of rubber. It protects the spring leaf against sudden impacts on the vehicle body and cushions metal-to-metal shocks during extreme compression. In addition, the leaf spring is characterized by its camber, which is the deflection of the leaf spring at its center, measured from the central line passing through the two eyes, which are the attachment points of the spring.

The Figure 1 illustrates all the details of the leaf spring. Each mentioned element affects the characteristics of the leaf spring, particularly its stiffness, meaning that any change in these elements results in a change in the spring's characteristics.

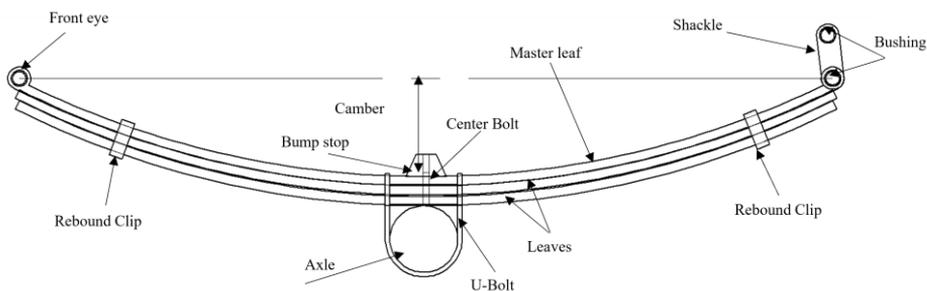


Figure 1 Leaf spring components

Leaf springs are classified based on several criteria. They can be classified according to the number of leaves they contain. Single-leaf or mono-leaf springs are commonly found in light vehicles such as passenger cars, vans, and some light trucks. Multi-leaf springs, made of several graduated leaves, are used across various vehicles including trucks, trailers, and some heavy-duty vehicles. In contrast to conventional leaf springs that maintain a uniform thickness throughout, tapered leaf springs are thicker in the center and gradually taper towards the ends. They are commonly used in various vehicles, including trucks, trailers, and some passenger cars.

Leaf springs also vary according to their structure such as semi-elliptical leaf springs, quarter elliptical leaf springs, three-quarter elliptical leaf springs, full elliptical leaf springs, transverse leaf springs, and cantilever-mounted semi-elliptic [3]. Additionally, they can have different rates, ranging from single-rate to variable-rate [6].

Various configurations exist to achieve a variable rate, including dual-rate helper springs, dual-rate extended leaf springs, progressive multi-leaf helper springs, progressive taper leaf helper springs, progressive dual-rate fixed cantilevers, and progressive dual-rate swing cantilevers [3].

Leaf springs present a challenge in design to achieve desired characteristics such as vertical stiffness, torsional stiffness ...etc. Several methods have been developed to model the leaf springs and determine their characteristics. Among them: beam theory, the finite element method (FEM), discrete methods...etc.

Beam theory studies the leaf spring as a beam to determine its characteristics, where several beam theories have been used for this purpose such as Timoshenko's theory [7] or by applying the second theorem of Castigliano [1].

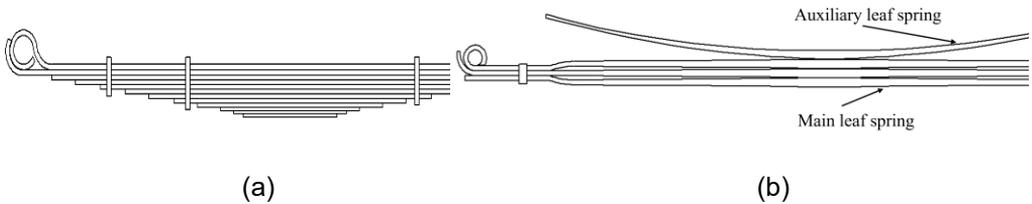
ADAMS Software employs the discrete method to determine the stiffnesses of the leaf spring. This method involves dividing the leaf spring into rigid elements, which are subsequently linked together using components such as torsion springs and dampers. The properties of these torsion springs and dampers are then refined until the force-displacement behavior of the modeled leaf spring matches or closely resembles, the actual force-displacement behavior of the physical leaf spring [4].

This paper aims to model and validate a truck's leaf springs, which are placed in the front and rear suspension in the ADAMS software. It aims to validate the model by comparing the vertical stiffness of the leaf springs obtained through simulation in ADAMS and analytical results using the beam theory with other results represented in the drawings considered reference values.

1 DESCRIPTION OF VEHICLE SUSPENSION

The Truck has a dependent suspension system in both the front and rear. The front and rear suspensions are structurally identical, each containing an axle connecting the two wheels, a shock absorber, and a leaf spring. The difference between them lies in the position of the shock absorbers relative to the axle and the type of leaf spring. The leaf spring used in the front suspension is a multi-leaf type with 12 graduated leaves, as shown in Figure 2 (a). The rear suspension comprises a dual-rate helper spring. It includes a main leaf spring of taper type with 03 leaves and an auxiliary leaf, a single taper leaf that comes into operation when the truck is subjected to a specific load, as shown in Figure 2 (b).

Detailed drawings provide all the details of the front and rear leaf springs. Based on these drawings, we can create a model of ADAMS\CAR's front and rear suspension.



(a) (b)
Figure 2 (a) Front leaf spring; (b) Rear leaf spring

2 MODELING OF LEAF SPRING IN ADAMS\CAR

Modeling a system in ADAMS\CAR follows a specific process that begins with creating models in the 'template', defining the major roles such as suspension, leaf spring, anti-roll bar, steering, etc. In these models, all details are provided, including hardpoints, element geometry, Attachment (joints and bushings), characteristics of shock absorbers and springs, and communicators (input and output) which have an important role in defining connections with other subsystems. Afterward, the creation of 'subsystems' based on previously created 'template', specifying minor roles such as front, rear, or any other role, where modifications can be made to the hardpoint, attachments, property files of the shock absorbers, springs, etc. After creating subsystems, they can be assembled into a "Full vehicle assembly" or "suspension assembly".

To assemble the rear truck suspension in ADAMS, three templates are created. The first template defines the axle with the shock absorber, specifying the 'suspension' as the major role. The second and the third templates represent the main and auxiliary leaf springs of taper type, with 'leaf spring' defined as the major role, with inputting all the characteristics of the leaf springs in the toolkit. Then, subsystems are created for each template, specifying 'rear' as the minor role.

For the front suspension, two templates are generated, following the same procedure as the rear suspension modeling, and changing the type of leaf spring which is a multi-leaf spring. Additionally, the subsystems are created by defining the minor role for both subsystems (axle with shock absorber and leaf spring) as 'front'.

The next step is to create a 'Suspension Assembly' for each leaf spring to proceed with the simulation and determine the stiffness of each one.

To model a leaf spring in ADAMS\CAR, there is a toolbox where all characteristics of the leaf spring can be entered. These parameters are the coordinates (x , z) and the thickness of each leaf, the characteristics of the shackle and clips, and the positioning of the leaf about the axle, bushing, and more.

The leaf spring model is automatically generated with details such as shackles, clips, bushings, seals and communicators.

The details of the three leaf springs are represented in the drawings. However, extracting the coordinates directly from these drawings is impossible due to the deflection of the installed spring in the truck ($z_c = \delta$), as shown in Figure 3(b), which is different from that represented in the drawing where there is no deflection ($z_c = 0$) as shown in Figure 3(a).

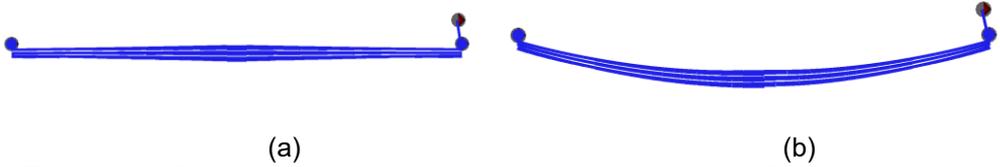


Figure 3 (a) Illustrated Configuration in the Drawing, (b) The Installed Configuration.

To determine the coordinates (x, z) of each leaf, as installed in the truck, we conducted geometric modeling of the master leaf, as detailed in Figure 4. The coordinates of the other leaves are then deduced from those of the master leaf.

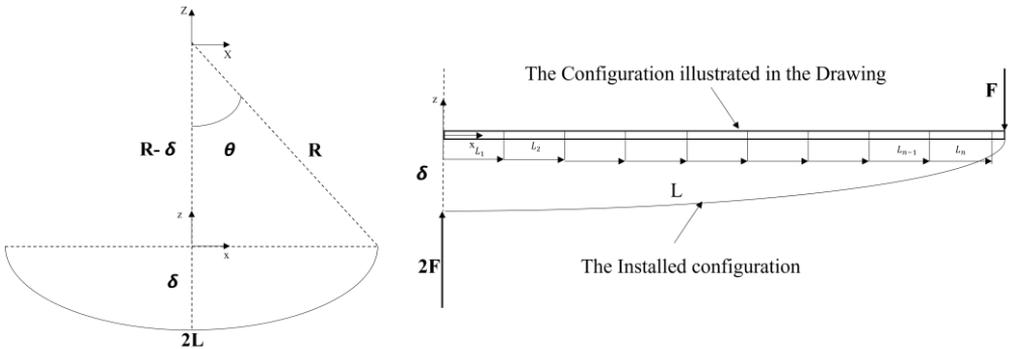


Figure 4 The geometric approach

Where δ represents the deflection, F is the force applied by the body on one side of the leaf spring, L_i are the lengths presented in the drawing, R and θ represent the radius and angle of the arc created when the master leaf is deflected, respectively, which are unknowns and $2L$ represents the total length of the master leaf as provided in the drawing.

According to the geometry presented in Figure 4, a system of equations (1) and (2) is extracted to describe the relationships between the parameters.

$$\frac{L}{2} = R\theta \tag{1}$$

$$\cos(\theta) = \frac{R - \delta}{R} \text{ and } \theta \in \left[0, \frac{\pi}{2}\right] \tag{2}$$

From equations (1) and (2), the function $f(R)$ is defined and presented in the equation (3):

$$f(R) = \cos\left(\frac{L}{2R}\right) - \frac{R - \delta}{R} \tag{3}$$

By solving $f(R) = 0$, both the radius R and angle θ of the of curvature are determined and the coordinates (x, z) are found using the equations (4),(5), and (6).

$$\theta_i = \frac{L_i}{2R} \tag{4}$$

$$x_i = R \cdot \sin(\theta_i) \tag{5}$$

$$z_i = R(1 - \cos(\theta_i)) - \delta \tag{6}$$

Numerical calculation based on the previously mentioned equations is necessary to find the coordinates (x, z). These coordinates are determined using the measured deflections for each leaf spring as installed in the truck, represented in Table 1.

Table 1 The measured deflection of the leaf springs

	Front leaf spring	Main rear leaf spring	Auxiliary rear leaf spring
Deflection δ (mm)	5	130	85

The next step involves inputting the coordinates of each leaf and additional characteristics as detailed in Table 2 into the leaf spring toolkit within ADAMS \CAR.

Table 2 The characteristics of leaf springs

		Front leaf spring	Rear leaf spring	
			Main	Auxiliary
leaves Number		12	3	1
Leaf type		Multi-leaf	Taper leaf	
Shackle	Length (mm)	98		/
	location	Rear		/
Clips	Number	4	2	/
Axle mount type		Over slung		
Eye shape		Downturned	Upturned	/

The leaf spring will be generated automatically within the template and saved as ‘leaf spring’, as shown in Figure 5. It can then be assembled with the axle to create either the front or rear suspension.

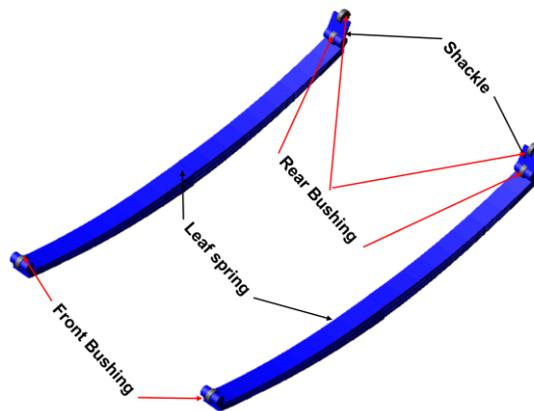


Figure 5: The created leaf spring in ADAMS

3 RESULTS AND DISCUSSION

Generally, the process to determine the vertical stiffness of leaf springs is to apply a vertical force (F) through an actuator at the center of the leaf spring and translation joints are applied at the eyes of the leaf spring, to allow only horizontal translation, as shown in the Figure 6. The corresponding displacement of the center of the leaf (dz) is measured and the vertical stiffness (K) of the leaf spring is determined by plotting the curve $F(dz)$.

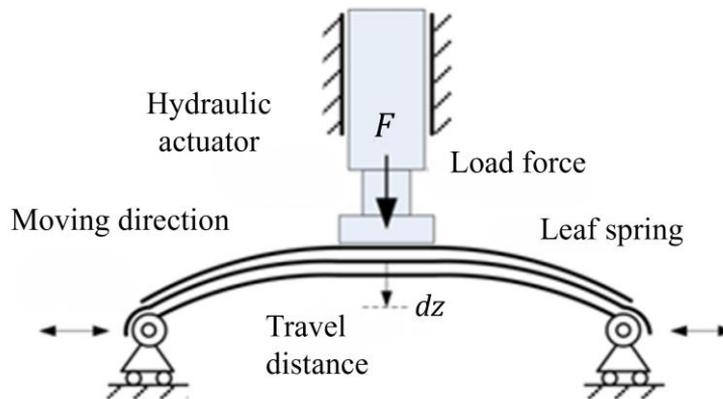


Figure 6 Procedure for determining vertical stiffness of the leaf spring [5]

3.1.1 ADAMS\CAR:

In ADAMS\CAR, to realize the suspension assembly as shown in Figure 6, translation joints between the eyes of the leaf spring and the ground will be added. The automatically generated bushings during leaf spring modeling will be deactivated, and the shackle will be ignored. The next step involves creating a subsystem for each leaf spring and assembling them with the axle and shock absorber in the ‘Suspension assembly’. At this stage, all three assemblies are ready for simulation.

Parallel Wheel Travel is conducted to determine the vertical stiffness of each leaf spring. In this simulation, vertical displacement is imposed by defining the upper and lower limits of wheel center displacement, known in the software as ‘Bump travel’ and ‘Rebound travel’. When the truck wheels are in contact with the ground; the leaf springs only function under compression. However, when they lose contact with the ground, which is unfavorable, the leaf springs are subjected to traction, which is not taken into account. Therefore, the lower limit value is considered to be zero.

The assemblies with the corresponding force-displacement curve for each leaf spring are represented in Figure 7.

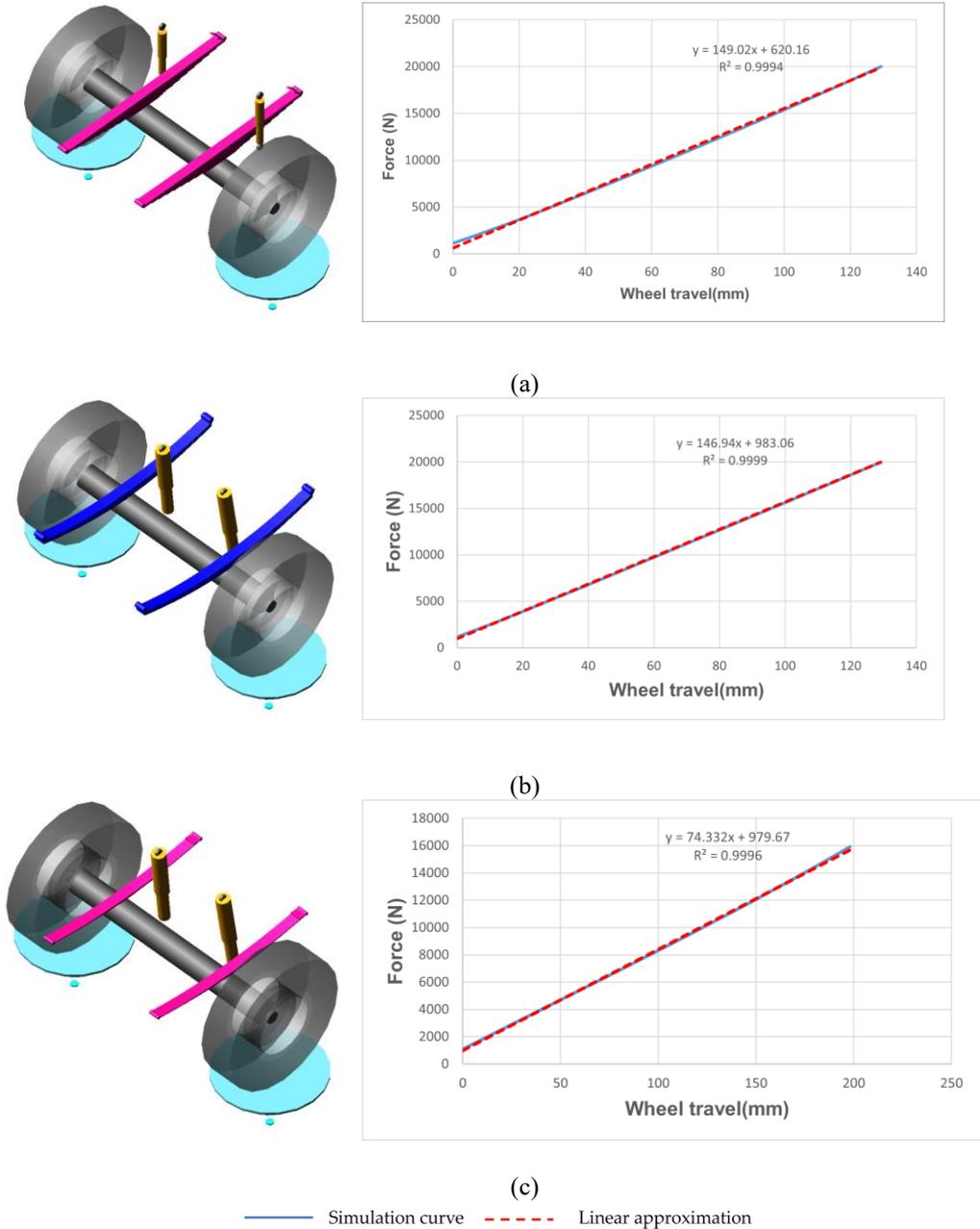


Figure 7 Assemblies and their corresponding Force-Displacement curves, (a) Front multi-leaf spring, (b) Rear main taper leaf, (c) Rear auxiliary Single taper leaf

From the simulation results for each leaf spring, as shown in Figure 7, it can be observed that the force-displacement curves are linear ($R^2 \approx 1$). Comparing the three curves, it's evident that the curves of the taper leaf suspension (Figure 7 (b) and Figure 7 (c)) exhibit perfect linearity compared to the curves of the multiple-leaf suspension Figure 7 (a), which initially shows a linearity issue before becoming perfectly linear. This observation can be attributed

to the behavior of the leaf spring: in the case of taper leaf springs, all the leaves react simultaneously when a force is applied.

Conversely, during the excitation of the multi-leaf spring containing graduated leaves, the leaves do not react simultaneously at the beginning of the excitation. However, when the applied force reaches a certain threshold, all the leaves react, resulting in a perfectly linear force-displacement curve. Therefore, we can conclude that the vertical rigidity coefficients remain practically constant during the excitation.

3.1.2 Beam theory:

The vertical stiffness of each leaf spring can be calculated using an analytical method commonly found in the literature based on beam theory. Based on the symmetry property of the leaf spring, beam theory is applied to the half-leaf spring to calculate its vertical stiffness. In this approach, one end of the half-leaf spring is fixed while a force is applied to the other, as presented in Figure 8. Then, the vertical stiffness is deduced by dividing the force by the deflection at the end of the beam.

Based on [10,11] and using Castigliano's theorem [1], the vertical stiffness of each leaf is calculated.

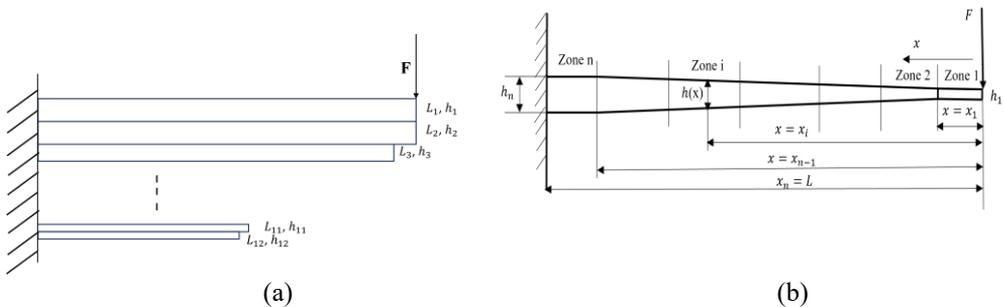


Figure 8 The half model of the leaf spring (a) multi-leaf spring and (b) mono-taper leaf spring

The analytical expressions for the vertical stiffness of a multi-leaf spring and a mono-taper leaf spring are given in the equations (7) and (8), respectively.

$$K = \frac{bE}{4 \sum_{i=2}^m \frac{(L-L_i)^3 - (L_1-L_{i-1})^3}{h_1^3 + h_2^3 + \dots + h_{i-1}^3} + \frac{L_1^3 - (L_1-L_m)^3}{h_1^3 + h_2^3 + \dots + h_{i-1}^3 + h_m^3}} \tag{7}$$

$$K = \frac{bE}{12 \left[\frac{x_1^2}{3h_1^3} + \frac{x_n^2 - x_{n-1}^2}{3h_n^3} + \sum_{i=2}^{n-1} \frac{1}{a_i^3} \left(Ln \left(\frac{h_i}{h_{i-1}} \right) + 2b_i \left(\frac{1}{h_i} - \frac{1}{h_{i-1}} \right) - \frac{b_i^2}{2} \left(\frac{1}{h_i^2} - \frac{1}{h_{i-1}^2} \right) \right) \right]} \tag{8}$$

Where:

a_i and b_i are the coefficients that define the linear expression of the height in each zone for the taper leaf spring, as given in (10) :

$$h = \begin{cases} h_1 & 0 \leq x < x_1 \\ a_i x + b_i & \text{if } x_1 \leq x < x_{n-1} \\ h_n & x_{n-1} \leq x < x_n \end{cases} \quad (9)$$

- E : Elastic modulus of materials;
- b : Width of the leaves;
- m : Number of leaves;
- n : Number of zones in taper leaf.

To find the vertical stiffness of the main leaf, we either transform the leaf spring with three leaves into a mono-taper leaf spring where we calculate the equivalent thickness of the new leaf.

According to [10], the equivalent thickness can be found using the expression (10), this thickness is used in the equation (8) to calculate the vertical stiffness of the main taper leaf.

$$h_e(x) = \sqrt[3]{h_1^3(x) + h_2^3(x) + h_3^3(x)} \quad (10)$$

Through the comparison of the vertical stiffness of each leaf using the simulation and analytical methods with the reference value, as shown in Table 3, the error between the simulation and the reference values does not exceed **11%**, which is in the acceptable range.

Table 3 Comparison between the simulation and the analytical with the reference results of vertical stiffnesses of the leaf springs

Emplacement	Type of spring	Reference stiffness (N/mm)	Analytical stiffness (N/mm)	Error (%)	Simulation stiffness (N/mm)	Error (%)
Front spring	Multi-leaf spring	141.95	154.436	8.80	149.02	4.98
Rear spring	Main taper leaf spring	148.59	157.60	6.06	146.94	1.11
	Auxiliary single taper leaf spring	67.25	65.30	2.90	74.33	10.52

4 CONCLUSIONS

This paper modeled the front and rear suspension of a (4x4) truck, each comprising an axle, a shock absorber, and a leaf spring. Due to the complexity of modeling the leaf spring in the ADAMS software, it was necessary to validate the model beforehand. The front suspension incorporated a multi-leaf spring consisting of 12 graduated leaves. In contrast, the rear suspension has two taper leaf springs: a main spring with 03 leaves and an auxiliary mono-leaf spring.

This validation process involved comparing the vertical stiffness values of the modeled leaf springs with those calculated using beam theory and the values provided in the engineering drawings which served as reference values.

A 'Parallel Wheel Travel' simulation was conducted for each type of leaf spring using ADAMS software to determine their vertical stiffness. The comparison indicated that the

error between the simulated and analytically calculated vertical stiffness values with the reference values, were within acceptable limits. Consequently, the front and rear suspension models are validated, enabling us to use them in the complete truck model.

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