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Development of an adaptive composite leaf spring

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ABSTRACT

As suspension of vehicles is generally designed for maximum load, its driving performance for light loaded cases is poor. Additionally, a hard suspension leads to dynamic peak loads on the vehicle structure and freight resulting in an increased noise level. Hence especially in trucks adjustable pneumatically driven suspension systems are commonly used. However, these systems are high maintenance and expensive compared to classic metallic leaf springs.

Within the research of the collaborative research centre (SFB) 639 an innovative adaptive lightweight suspension system consisting of glass fibre-reinforced polypropylene (GF/PP) leaf spring elements is designed. Via a component integrated hydraulic system different levels of stiffness can be applied to the spring element depending on the loaded mass and road properties in order to reduce accelerations of the load platform and vibration peaks of the freight. Especially when transporting loose freight a reduction of mass acceleration is a basic possibility to reduce noise emission.

Through a detailed multi-body simulation of a demonstrator vehicle, reduced amplitudes of platform acceleration and dynamic wheel loads were determined when using the novel suspension system. Considering multiple operation conditions, the ascertained results indicate a significant reduction of noise emission.

Keywords: Suspension, Composite, Transportation noise
I-INCE Classification of Subjects Number(s): 13.2.4

1 INTRODUCTION

As the number of vehicles on worldwide streets is still growing, disturbance caused through traffic noise is getting a significant problem of environmental health protection. Over years numerous studies made in different countries have been proofed that noise produces both psychological and physical stress, causes sleep disturbance and lowers life quality [1, 2, 3]. Thus focus is set on the enhancement of traffic noise in order to protect residents and drivers. Besides the use of passive noise protection, like constructions of sound protection panels and walls which are generally built up close to highways and highly frequented roads, noise radiation can be lowered through design features of the vehicle itself very efficiently. Compared to passenger cars, especially trucks emit a much higher noise level [4].

Besides the main noise radiation sources of a truck, such as engine and tire-road interaction, a significant amount of noise is emitted through vibrations of chassis and load, too [5]. In order to reduce shocks and vibrations of the car body triggered through the different road profiles, focus is set on the design of a well-adaptable suspension system. In order to adjust a truck to different road and load conditions adaptive pneumatically driven suspension systems are commonly used. However, compared to classic non-adaptable metallic leaf springs these systems require high maintenance.

Within the research of the collaborative research centre (SFB) 639 an innovative adaptive lightweight suspension solution of a composite fibre-reinforced leaf spring element is developed. Outstanding properties, e.g. high strength, low specific mass and the possibility of high functional integration, make this material group very well suitable to allow stiffness adaption using the classical leaf spring design.

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2 CONCEPT AND DESIGN OF ADAPTIVE COMPOSITE LEAF SPRING

The aim of the presented research project is to invent an easy low maintenance leaf spring featuring changeable stiffness properties. Furthermore, lightweight potentials should be exhausted by the use of textile thermoplastic composites. Featuring a very high and directional adjustable stiffness a bar of glass fibre-reinforced polypropylene (GF-PP) was chosen as basic substructure. Hence, the spring is able to resist high tension and compression stresses when bended featuring a comparable low mass at the same time. In order to realize adaptive stiffness properties a fluid filled cavity is integrated into the substructure as shown in figure 1. Through pressure variation of an internal fluid the stiffness of the spring element can be varied.

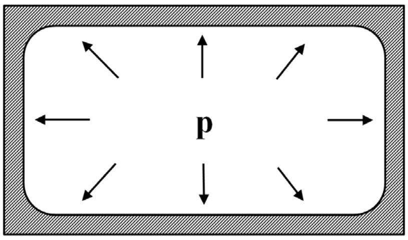

Figure 1 – Functional principle of the fluid filled composite spring element

When bending the spring element, delamination of the composite material may occur due to complex shear stresses affecting the side walls. Hence multiple different design models were made and analysed to avoid delamination. Finally a multi-material approach was chosen using aluminium fillets as side wall construction while top and bottom wall still consist of GF-PP hybrid-yarn-textile-thermoplastic (HYTT) composites which are made of multi-layered flat-knitted fabrics (MKF). The textile layers are set up in a symmetric layup of $[0/90//90/0]_{2S}$. The final design of the multi- material leaf spring containing composite belts, aluminium fillets and fluid filled cavity is shown in figure 2. All different components are joined through high performance glue. The cavity bag consists of a highly resistant elastomer.

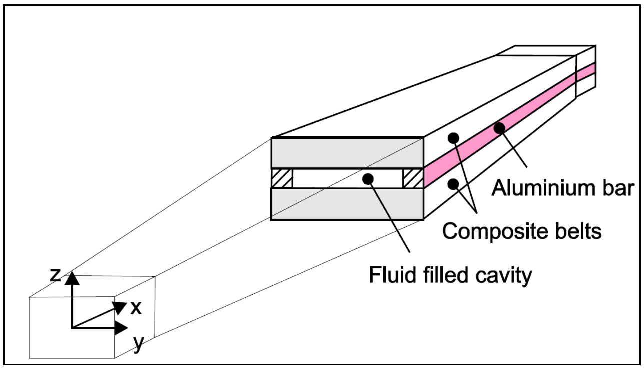

Figure 2 - Cross section of the multi-material leaf spring

Besides the mentioned components, the developed adaptable spring element is able to operate without any other complex mechanical parts. Furthermore low energy functionality can be ensured during vehicle operation as the inner fluid pressure can easily be kept constant when simply closing the fluid system. A further advantage is the low mass of the composite system compared to conventional adaptive suspension systems.

3 MULTI-BODY SIMULATION

3.1 Model set-up

In order to analyse the functionality of the invented spring element and to analyse the influence on the entire vibration system of a transportation vehicle, a multi-body simulation is used. The main aim is to study the effects of an adaptive spring rate on the vibration behaviour of the vehicle superstructure. With the use of the commercial software package *SimulationX*, a detailed simulation model of a demonstration vehicle named “FiF” (shown in figure 3(a) and presented in [6,7]) was built up. Behind the illustrated 3D-model stands an arrangement of multiple connected mass, spring and damper elements shown in figure 3(b).

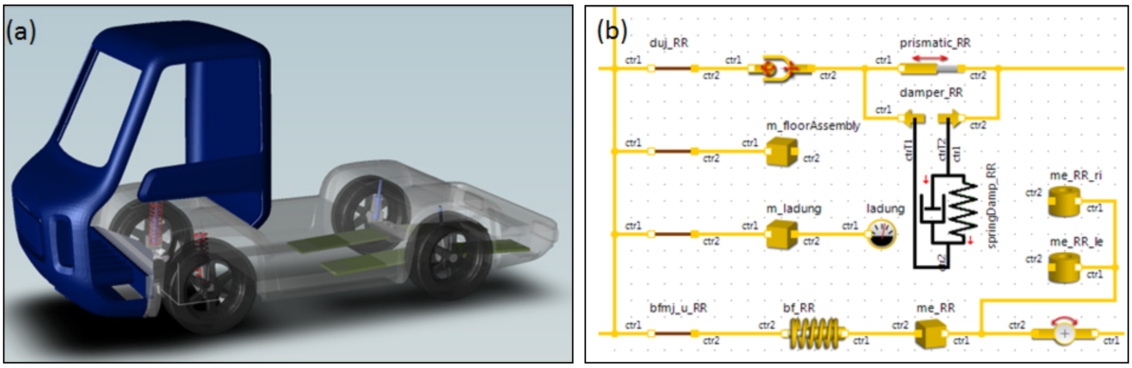

Figure 3 – (a) 3D-model of the demonstrator vehicle „FiF“, (b) Detail of the multi-body simulation model

High attention was paid on a realistic set-up of the the suspension kinematics shown in figure 4(a). Furthermore figure 4(b) illustrates a simple 2D-scheme of the multi-body model including the adujstable rear suspension. Other variable input values, e.g. road profile (z) and additional load, are indicated, too.

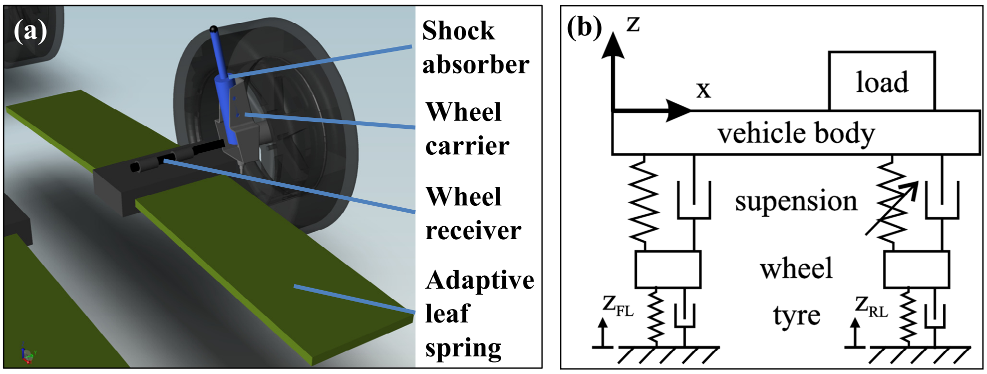

Figure 4 - (a) Components of the rear wheel suspension, (b) Simplified 2D-scheme of the multi-body model

3.2 Input variables

After having built up the entire model, the chosen input variables are used to run different simulation scenarios. In order to simulate driving, the model is excited through a road profile function, defined by a time dependent translatory displacement of the tires in z-direction (see z_{FL} and z_{RL} in figure 4(b)).

First of all, a harmonic excitation signal is applied onto the wheels in order to analyse the system response within a continuous spectrum of excitation frequencies. A frequency range from 0 Hz - 20Hz is chosen featuring constant amplitudes of 80mm.

Secondly, referring to ISO 8608: 1995 (E), road profiles of different qualities have been generated in order to analyse realistic driving scenarios. The generated tracks represent potholes and bumps with irregular depth and distances to another. Figure 5(a) shows an example of two generated road profiles of different qualities. Representing the road conditions of a highway as well as the profile of a construction side, both profiles were generated randomly using a special coded MATLAB macro. For the scenario to be analysed in this paper, the road profile function of the construction site is set as input variable.

A further important input-variable is the mutable stiffness of the adaptive leaf spring according to the internal fluid pressure. Through the results of previously made numerical simulations the dependency between inner fluid pressure and stiffness was calculated and determined to be almost linear. Figure 5(b) shows the calculated characteristic curves of the used adaptable spring.

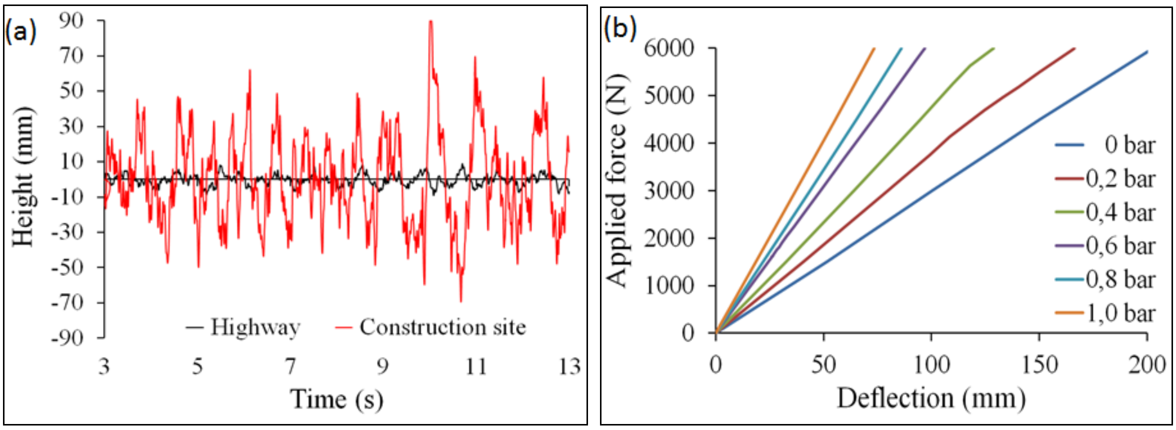

Figure 5 – Different types of road characteristic functions (a) and characteristics of the adaptive composite leaf spring (b)

Furthermore, all used parameters of the chosen scenarios are listed below in table 1.

Table 1: Set parameters of the chosen scenarios

Parameter	Value	
Excitation function	Harmonic	‘Construction site’
Frequency range/ time	0Hz-20Hz	13 s
Driving speed	-	13 m/s
Cavity pressure	0 bar; 0,6 bar; 1 bar	
Additional load	500 kg	

3.3 Defining relevant output variables

Within this paper, attention is given to the noise emission of a transportation vehicle caused through shocks and vibrations depending on the road profile only. Assuming a loaded truck driving along a construction site or on streets of poor quality, major part of the produced noise would be caused through rattling of loose parts of the vehicle superstructure and freight.

Rattling of loose parts on the platform occur if the platform acceleration is smaller than gravity, meaning if $a < g$ with $g = -9{,}81\ \mathrm{m/s^2}$. In order to reduce the emitted noise level, a softer suspension can be used to decrease acceleration amplitudes within the range of low eigenfrequencies of the vehicle body [8]. As adaptive stiffness properties mainly affect the suspension system in vertical (z-)direction, focus is set on the analysis of the vertical components only. Hence especially the vertical platform acceleration is taken into account and is going to be analysed within time and frequency domain.

Furthermore it is well known that the deflection of a spring increases when lowering its stiffness. Hence, the rear part of the superstructure would be lowered maximal when using a soft suspension. In order to ensure transport safety, the deflection needs to stay within a predefined limit and has to be analysed, too. For the designed suspension system a deflection limit of +150 mm and -170 mm in z-direction is assumed referring to automobile standards.

Besides, another fundamentally function of a suspension system is the attenuation of dynamic load amplitudes affecting components of the chassis. Hence, dynamic loads affecting the wheel receiver adapter are analysed as well.

3.4 Generated results

In order to interpret vibration behaviour accurately, first of all eigenfrequencies of the multi-body simulation model are determined. Due to its high inertia, the vehicle is mainly affected through low excitation frequencies of the road profile. Hence low-frequency eigenfrequencies are considered only. Table 2 gives an overview of the first three calculated modes of the model considering different suspension settings. It is shown, that all of the calculated eigenfrequencies are lowered with increasing spring stiffness.

Table 2: Calculated eigenfrequencies of the simulation model

Mode	Eigenfrequency, Hz		
	0 bar	0,6 bar	1 bar
1st	0,016	0,012	0,01
2nd	2,51	2,48	2,47
3rd	75,21	75,09	75

To investigate the frequency dependent vibration behaviour of the vehicle platform, first of all, the transmission function of the suspension system is analysed. For this purpose the simulation model is excited via harmonic road excitation with amplitudes of 80mm within a frequency range from 0 Hz – 20 Hz. Frequency-specific conclusions can be found when transferring the response function into the frequency domain via Fast-Fourier-Transformation (FFT). Figure 6 shows a single-sided amplitude spectrum of the response function of the load platform. It can be seen that in particular the second eigenfrequency of the vehicle abets the maximum displacement amplitudes of the platform. Amplitudes within a range from 1 Hz – 3 Hz are increased significantly. However, considering different suspension settings it is obvious that maximum amplitudes can be lowered when using a softer suspension. Within the second eigenfrequency range the maximal vertical displacement can be decreased by up to 30%. Furthermore, for excitation signals higher than 4 Hz different suspension set-ups do not affect the vibration behaviour of the vehicle superstructure anymore.

As the acceleration is the second derivative of the displacement, a similar conclusion can be found for acceleration amplitudes of the vehicle platform. Thus platform accelerations in a range from 1Hz-3Hz can be decreased significantly using a softer suspension system, too.

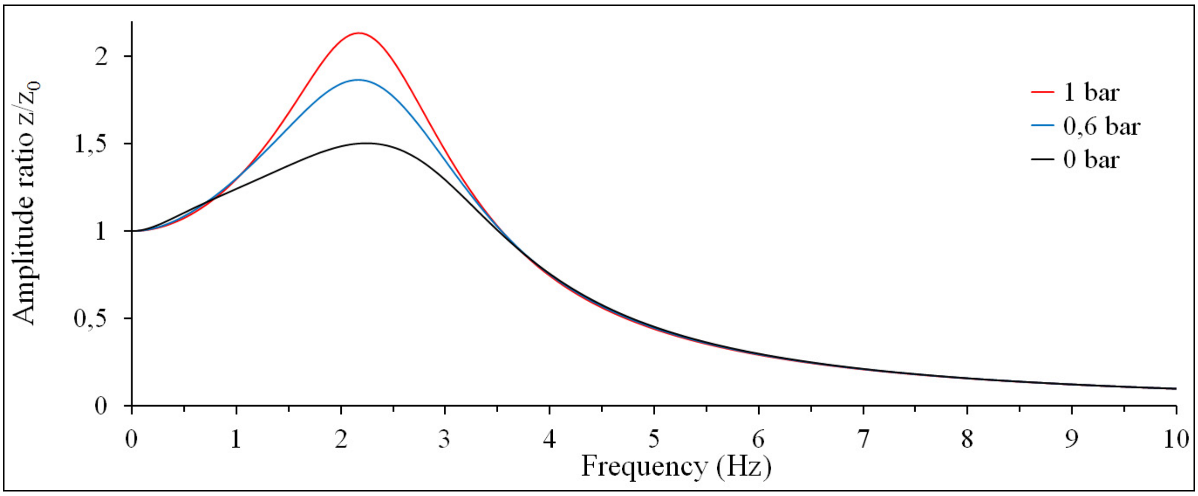

Figure 6 – Response characteristics of wheel excitation (z_0) and load platform displacement (z) considering different suspension settings

Secondly a driving scenario considering a realistic road profile of a construction site (see figure 5(b)) is simulated. Figure 7 shows the absolute values of the vehicle platform acceleration and compares two time-dependent response functions of a soft and a hard suspension setting ($p = 0$ and 1 bar). For comparison, the gravity constant g ($g = -9{,}81\,m/s^2$) is represented by the blue bar. If the acceleration of the platform is smaller than gravity ($a_{platform} < g$), the loose mass situated on the load platform of the vehicle will loose contact and hence will cause noise when dropping.

It is shown that acceleration amplitudes within this realistic scenario are reduced by up to 15% when minimising the stiffness of the rear suspension.

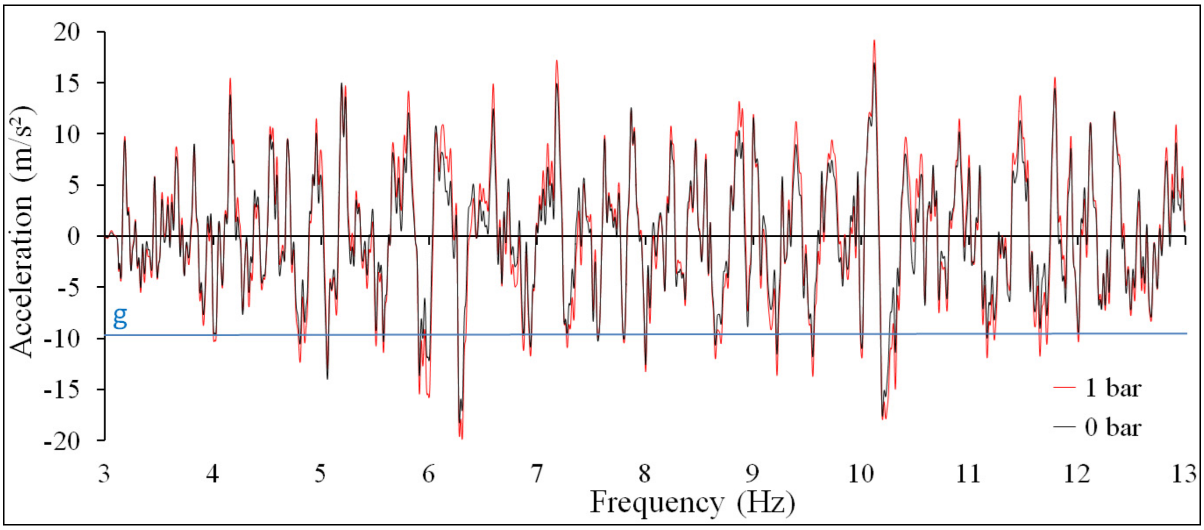

Figure 7 - Vertical acceleration of the loaded mass

Furthermore the vertical displacement of the rear vehicle body is analysed when driving with three different suspension settings (p = 0; 0,6 and 1 bar). Figure 8 shows the displacement functions of the vehicle platform. First of all, within the first three seconds the additional load is applied onto the model. It is shown that a decreased stiffness lowers the position of the superstructure by -120mm when only applying the predefined static load of 500kg. Viewing the second part of the graph, additional dynamically caused displacements can be observed featuring total displacements of 150 mm. However, when adding the displacement caused through static load, the predefined lower suspension limit of - 170 mm (indicated by the red bar) is reached when loading the soft suspension dynamically.

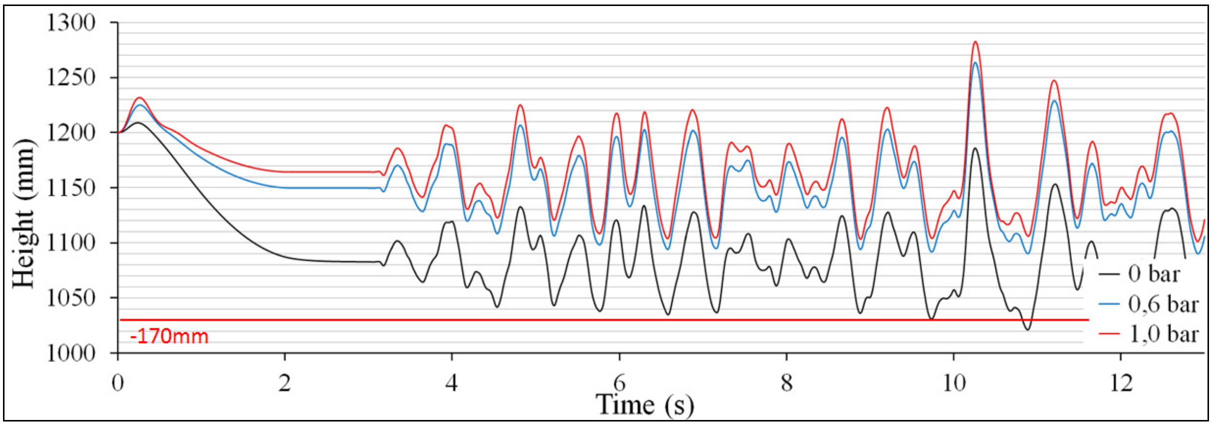

Figure 8 – Displacement of the vehicle platform in z-direction

Figure 9 displays the dynamic load in z-direction measured at the wheel receiver adapter (referring to figure 4(a)). Like in the previous examples, three different stiffness settings of the adaptive spring element are considered. The results indicate that the softer suspension lowers dynamic peak loads to more than 50% compared to the hard suspension setting. Thus durability of suspension components can be extended when adapting the suspension system according to freight load and road conditions.

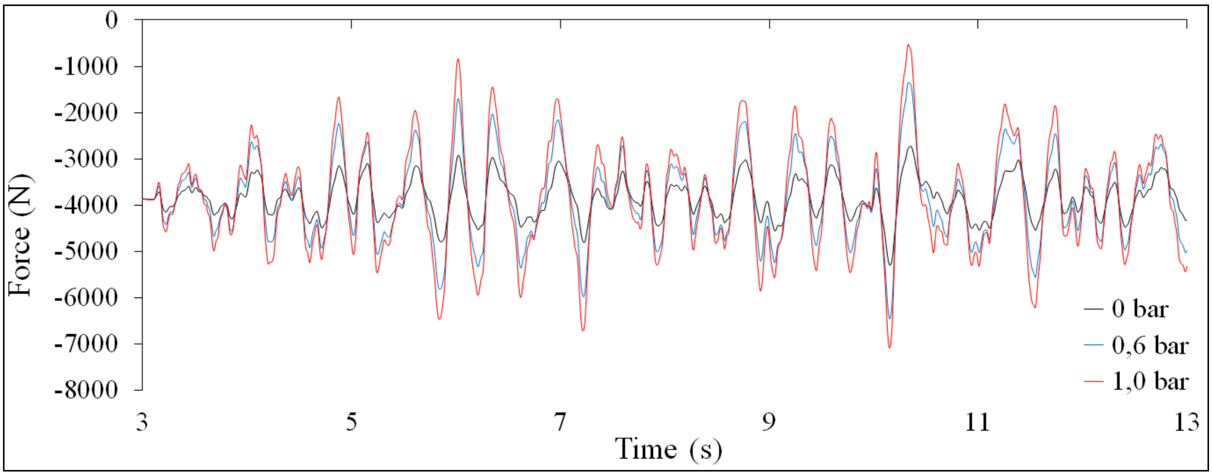

Figure 9 – Vertical load component acting at the wheel receive adapter when driving with different suspension settings

4 CONCLUSIONS

The presented paper shows that with the use of composite materials a cost effective and low maintenance solution of an adaptive leaf spring can be realised. The invented spring element consists of a multi-material mix out of glass fibre-reinforced polypropylene and aluminium including a pressurised cavity. The design was optimised to resist complex stresses and features a significant mass reduction compared to a conventional metallic leaf spring. Focus of this paper was set on an analysis of the shock and vibration behaviour of a transportation vehicle using the new invented adaptive spring element. For this aim a complex multi-body-simulation model based on an own invented demonstrator vehicle named “FiF” was set up including multiple variable input values. Through the use of the multi-body simulation relevant eigenfrequencies of the entire system were determined. Furthermore the effect of the adaptive suspension system was analysed in order to lower noise emission. The vertical acceleration of the vehicle load platform was defined to stand in direct relation to noise emission of the vehicle superstructure and loaded freight. The calculated results showed that a softer suspension can significantly decrease acceleration amplitudes within the low frequency range below 4Hz. Additionally it was shown, that a softer suspension can limit dynamic load impacts onto chassis components by more than 50%. In order to ensure vehicle operation, the displacement of the vehicle superstructure was analysed, too. It could be concluded that when using a soft spring suspension particular attention has to be paid on the vehicle-specific maximum deflection limit in order to ensure transport safety. Hence, besides the mentioned advantages of a soft suspension, a load dependent minimum stiffness has to be strictly adhered.

Summarized, with the new invented adaptive low-maintenance suspension solution for transportation vehicles, an optimal adaption to different load cases and road properties can be ensured. Thus, for future transport vehicle generations ride comfort and functionality can be improved significantly.

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