SUSTAINABLE LOGGING PROCESS BY A FORWARDER WITH AN INNOVATIVE HYDRO-PNEUMATIC SUSPENSION

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ABSTRACT

Forest machines enable a fast and save way to harvest the sustainable product wood. Especially forwarders have a huge impact on the forest site, as they have high wheel loads combined with frequent crossings. To enable a sustainable logging process, a new hydro-pneumatic suspended bogie axle is developed. In this paper, the suspended axle is evaluated and compared simulative to a standard in-market bogie axle without any suspension. Therefore, a simulation model of a forwarder with suspended bogie axles was built based on a validated model of an in-market forwarder. Both simulation models were driven over a skid road and a forest road. Dynamic wheel forces can be reduced with the suspended system up to 40 %. The maximum amplitude of vertical accelerations is reduced significantly with the hydro-pneumatic suspension up to one-third of the standard bogie. Furthermore, there is no significant Eigen frequency of the developed system compared to the reference system. As a result, not only soil damage can be reduced but also the working conditions of the operator can be improved with hydro-pneumatic suspended bogie axles.

KEYWORDS: Suspended bogie axle, forwarder, logging, hydro-pneumatic, Forwarder2020

1. INTRODUCTION

For a sustainable logging process in a fully mechanized timber harvesting chain such as the cut-to-length (CTL) logging system soil damages, e.g. rut formation and soil compression caused by a forwarders wheel load, have to be minimized as much as possible [1; 2]. Equalizing dynamic wheel loads with a suspended bogie axle leads to more steady vertical wheel forces [3]. Hence, more drive torque can be applied to the track while concurrently slip decreases, resulting in a lower impact on forest soils. Reducing simultaneously carriage vibrations creates a higher productivity and healthier working environment for the machine operator [4–6].

At the current state of technology bogie axles have established themselves in forestry machines to run over harsh, uneven ground terrain. Nevertheless, several efforts were made to improve forwarders regarding soil protection by implementing different axles, e.g. machines with a crawler chassis or suspended pendulum arms [7; 8]. In the EU project ‘Forwarder2020’ a new hydro-pneumatic suspended bogie axle has been designed to reduce dynamic wheel loads and cabin vibrations [9]. In the following contribution, the development of simulation models with standard and suspended bogie axles including their functionality is described. Based on this models, the new concept of a hydro-pneumatic suspended bogie axle is compared to a standard bogie regarding wheel loads, vertical acceleration and roll angle speed of the front carriage.

2. SIMULATION MODEL OF A STANDARD BOGIE AXLE

An eight-wheeled forwarder is simulated and validated with the Simscape modules of MATLAB Simulink. A standard in-market vehicle is implemented to receive a reference simulation model to investigate and compare new suspension systems. The reference machine is simplified to six rigid bodies and eight tyre model components. Two of the bodies represent the front and the back carriage of the vehicle, which are connected to each other by one rotational joint in driving direction. Hence, an independent roll movement of the front and back carriage is ensured. The pitch angle degree of freedom between the front and back carriage is restricted, so these two bodies have the same pitch movement, as derived from forwarder kinematics. The further rigid bodies represent the four bogies, one at each side of the front and back carriage. These are jointed in transversal direction to allow a pitch movement of each bogie. Any bogie can move independently and is connected by a rotational joint at its middle point to the frame of the vehicle and at the front and back ends to a tyre model, implemented by the Hohenheim Tyre Model [10; 11]. The Hohenheim Tyre Model was developed to investigate wheel forces and wheel deformations of a tractor vehicle, while driving over obstacles. The model is performed by a spoke model to reach a high resoluted calculation of uneven ground terrain [11]. It has been validated at the University of Hohenheim based on measurement data of a tyre test bench [10; 11].

In the present simulation, any tyre model connects the wheel hub of the vehicle with the ground and calculates the relative wheel forces and torques, which are imprinted to the multi body system of the vehicle. The calculation circuit is closed, as the deformation of the tyre resulting from wheel forces and moments, is sent from the multi body to the tyre model. The spokes of the model are orientated in radial direction and allow through the modelling as a non-linear spring-damper-system a good approximation of a real tyre. The interradial elements effect a deformation of the adjacent spoke elements if one spoke is activated, so they have a major importance for the calculation of the wheel forces while driving over obstacles. The geometric tyre parameters are adapted from the forestry machine and the kinematic parameters taken over from the standard tyre model to use the validated parameters of the tyre model. [10; 11]

To validate the present model of the standard bogie system, measurement and simulation results of a previous publication by [12] are compared to the simulation in this paper. The geometry of the vehicle simulated in [12] is derived from a Komatsu forwarder with a maximum loading capacity of 12 tons. Its dimensions are taken over to the presented model of an in-market machine to simulate with the same vehicle parameters. As driving terrain the “Skogforsk” test track was implemented, which is a frequently used test track for forestry machines [12] This track includes a 28-meter track profile with triangular-shaped obstacles of three different heights from 150 mm to 350 mm. The simulation model can be calculated with a full loaded forwarder or an unloaded forwarder, to compare the different impacts on the dynamic wheel forces and the vibration of the vehicle. To keep a constant velocity, the vehicle speed is set a desired value and regulated by a PID-controller for the engine torque. This controller is necessary due to the obstacles, which cause a force against the driving movement of the vehicle, thus a non-regulated vehicle velocity would possibly end in stoppage. By using the described controller, the vehicle velocity oscillates for example in a range of 14 % around the demanded speed of 1.8 km/h, very well comparable with the measurement data in [12].

The rotational speed of any wheel is calculated by one equation of motion, which uses engine torque and rolling resistances of each wheel as input variables and wheel inertia as parameter. Hence, every wheel rotates with the same speed as derived from the real bogie axle systems. The inertia of the whole vehicle translation is calculated by the multi body system. With the velocity-controller there is a simple way to vary the velocity of the vehicle in a parameter study and guarantee a constant speed level.

The resulting bogie angles, exemplarily for the front carriage, are compared in Figure 1 for a validation of the built simulation model with a standard bogie axle. The figure shows an accurate accordance between the already validated simulations of [12], marked as Reference Model, and the results of this paper. The small deviations are considered due to the usage of different tyre models. Bogie angles, roll angles of front and back carriage and pitch angle rate fits as well as shown for the bogie angle of the front carriage.

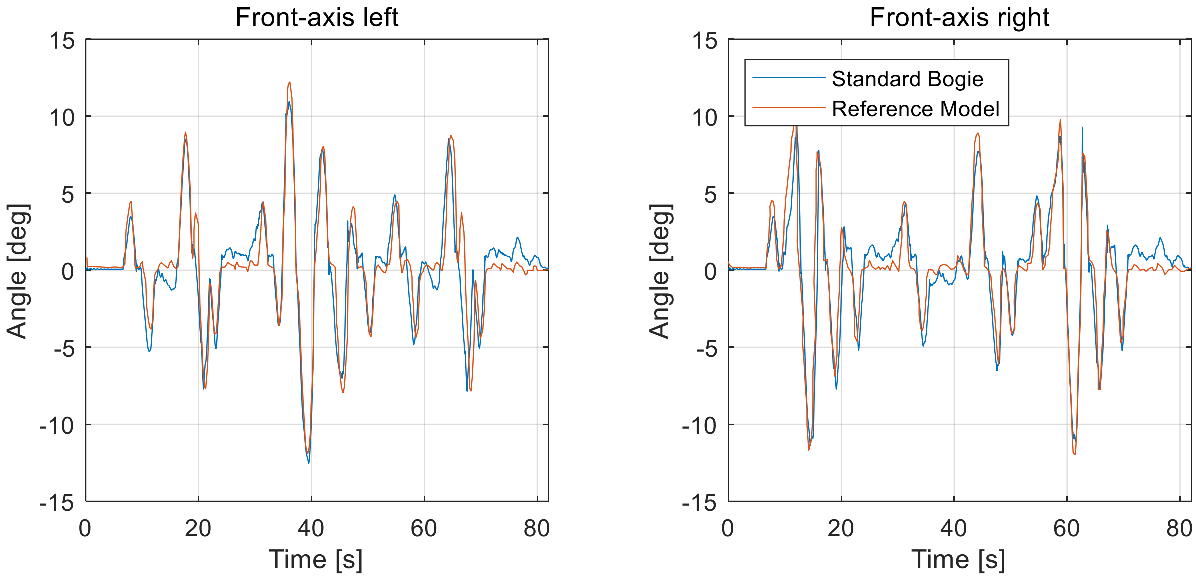

Figure 1. Bogie Angles at the front carriage at the Skogforsk test track driving with 1.8 km/h

With the validated simulation model including a standard bogie axle a possibility was created to implement new suspension systems and compare them to the standard system. Relevant values include for example the dynamic wheel forces or the vertical vibrations of the cabin in respect to the dynamic ground pressures and the driver’s comfort. In the next chapter a new suspended bogie system is described and simulated to compare its advantages to the standard bogie.

3. FUNCTIONALITY OF A HYDRO-PNEUMATIC SUSPENDED BOGIE

To increase the productivity of forestry machines and to minimize ground pressure due to lower dynamic wheel forces, a new suspended bogie axle has been designed for a forwarder with a maximum load of 11 tons by the company HSM [9]. This new bogie axle, illustrated in Figure 2, allows the usual bogie motion but includes an additional suspension system. The suspension system is developed as a hydro-pneumatic unit. The expected main advantages of the suspended bogie are beside the decrease of the dynamic wheel forces, less vibrations of the vehicle and a smoother rolling movement of the front and back carriage compared to the standard bogie.

In the suspended bogie, each wheel is connected to its own bogie and is able to rotate individually. Preserving the bogie axle principle, both pendulum arms of each side are attached to each other through a hydraulic cylinder. By blocking this cylinder, the new system reacts nearly like a standard bogie axle. If the cylinders can move freely, a relative displacement between the pendulum arms is possible and a suspension and damping force is generated. Accordingly, the vehicle has four cylinders, while the hydraulic piston side of each cylinder is connected to a pneumatic accumulator, which is prestressed to a required pressure level to reach the desired height of the vehicle frame, compare Figure 3. At each carriage, the left and the right bogie system is connected by a cross circuit, so the piston side of the left cylinder with its accumulator is connected to the rod side of the right cylinder. This allows an increase of the rolling stability as already known e.g. from front axle suspension systems of tractors [3]. Between the piston side and the accumulator an orifice is constructively used as a hydraulic damper to decrease pressure-vibrations.

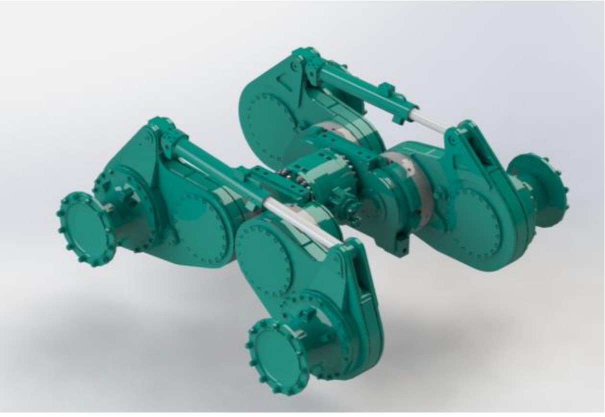

Figure 2. Suspended bogie axle © HSM [9]

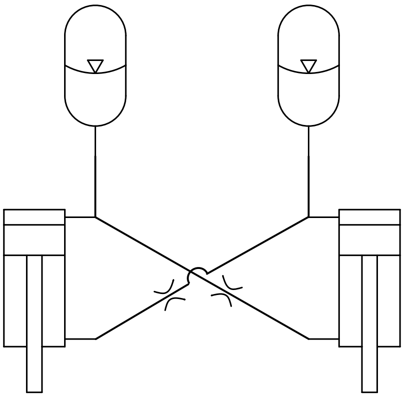

Figure 3: Hydraulic scheme of suspension [9]

To evaluate the advantages of this new system, a model of this suspended axle is implemented to the validated simulation model of the standard vehicle by replacing the standard bogie and keeping the vehicle dimensions of the Komatsu forwarder. The aim is to compare two equal vehicles with only different axle types. All parameters like vehicle mass and the velocity remain the same.

In Simulink the suspension system is build as a multibody and an additional hydraulic system. In contrast to the standard bogie, every wheel is connected to an own rigid body and can move independently, restricted by the connection of the bogie to the vehicle frame and the joint to the cylinder. The front and back carriage are connected as before and may only rotate in the rolling direction. The coupling between the hydraulic and the multi body model is implemented by a force-velocity coupling. The motion of the multi body is sent to the hydraulic system. The reaction force of the actuator is calculated in relation to the hydraulic pressure in cylinders and accumulators, which is given back to the linear joint in the multi body simulation. Figure 4 shows a possible installation situation in the forwarder. Both bogie axles are implement as hydro-pneumatic axles. The vehicle frame and dimensions can be retained with only minor changes.

Figure 4. Assembly situation in the forwarder © HSM [9]

The effects of the new suspension systems are discussed in the following chapter regarding the dynamic wheel forces, vibrations and accelerations of the vehicles front carriage. To give a conclusion and to ensure the comparability to the standard system, the results are always considered based on the validated simulation results of the standard bogie simulation.

4. EVALUATION OF THE SUSPENDED BOGIE

The suspended bogie axle was tested simulative under varying conditions regarding driving speed and road conditions.

4.1. Driving over the Skogforsk test track with 1.8 km/h

The main objectives of the hydro-pneumatic suspended bogie axle are to reduce dynamic wheel loads to improve soil protection as well as minimizing whole-body vibrations for healthier operator working conditions. Hence, in this section dynamic wheel loads, vertical accelerations and roll angles of the front carriage are evaluated to show the potential of a suspended bogie axle regarding the mentioned aims.

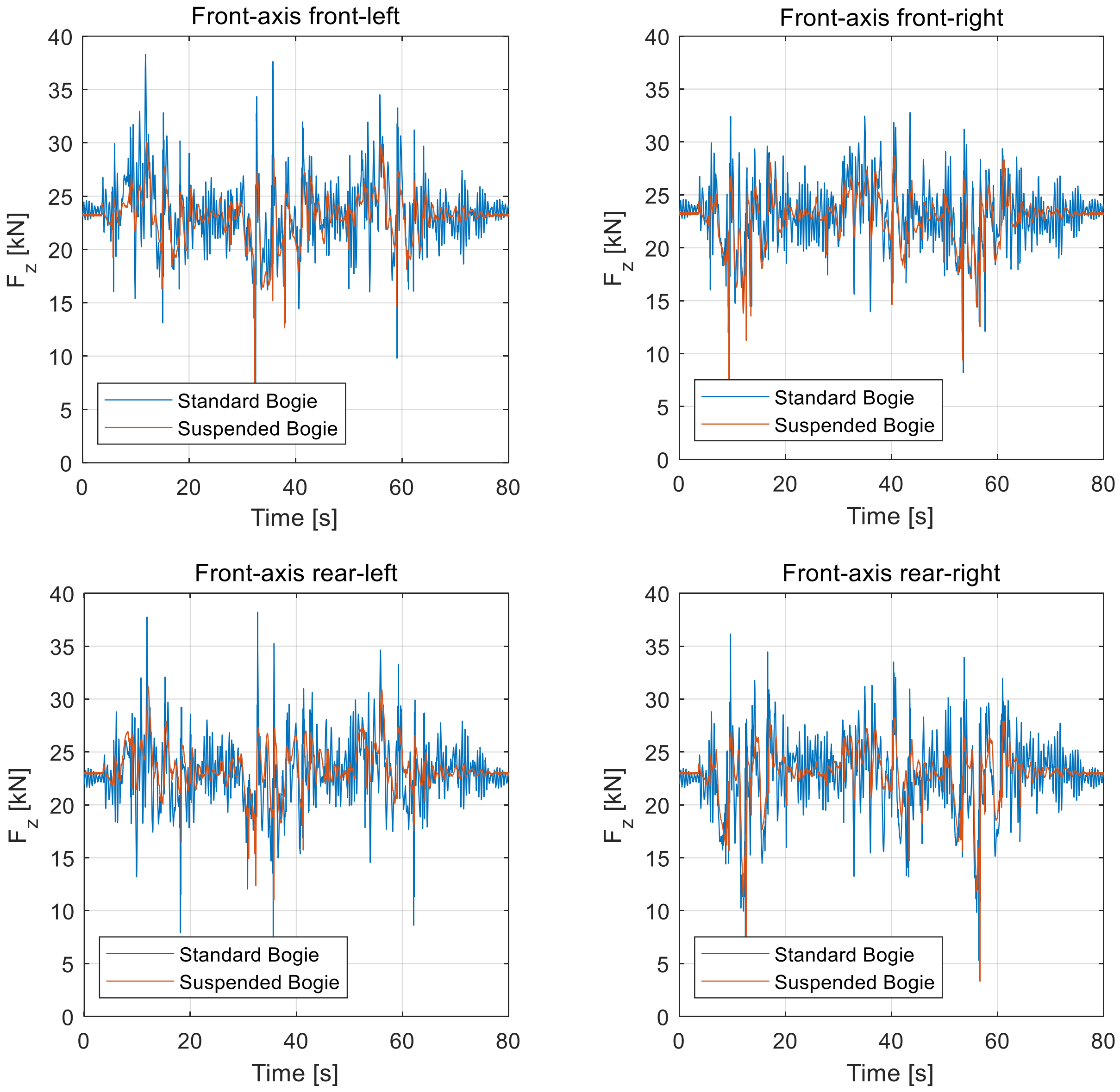

*Figure 5. Wheel forces at the Skogforsk test track driving with 1.8 km/*h

Both machines were driven simulative over the Skogforsk test track [12] with a vehicle velocity of 1.8 km/h. This represents a common driving speed at a skid trail. In Figure 5, wheel loads of the front carriage are displayed over time for the validated in-market machine and the suspended bogie axle while driving over the test track. With the suspended bogie, wheel load fluctuations are reduced significantly. Analysing exemplarily the front-left wheel of the front carriage, the maximum wheel load of the standard bogie is with 38.9 kN at

34.8 s about 62% higher than the static wheel load of 23.7 kN. With the suspended bogie, the maximum wheel load (29.7 kN at 55 s) is about 27 % higher than the static wheel load. Especially when driving over high obstacles (height of 0.35 m) for example between 31 s to 35 s, peak forces are minimized about 10 kN, which equals a reduction about 40 %. Driving fully loaded, this effect is magnified. The decreased fluctuation results also in less stresses for the chassis.

Another major improvement due to the suspended bogie can be seen in Figure 6, where the vertical accelerations of the front chassis are shown for the same passage of the test track. Relative vertical accelerations of the machine with the standard bogie varies between -1.9 m/s² and 2.4 m/s², shown via the blue graph. In comparison to this, the acceleration with a suspended bogie are in the range of -1 m/s² to 0.63 m/s². These describes a reduction to nearly one-third comparing the suspended bogie to a standard system. Same effect can be seen even better by transforming the accelerations from time domain into frequency domain via a standardized, discrete fast Fourier transformation, compare Figure 6. The main frequencies lay between 1.6 Hz and 2.4 Hz with the standard bogie, supplemented with two frequencies around 2.6 Hz and 2.9 Hz. In contrast, there are no main frequencies with the suspended bogie in this range. In general, the frequency spectrum is more distributed, with a minor shift to lower frequencies between 0.5 Hz and 1 Hz.

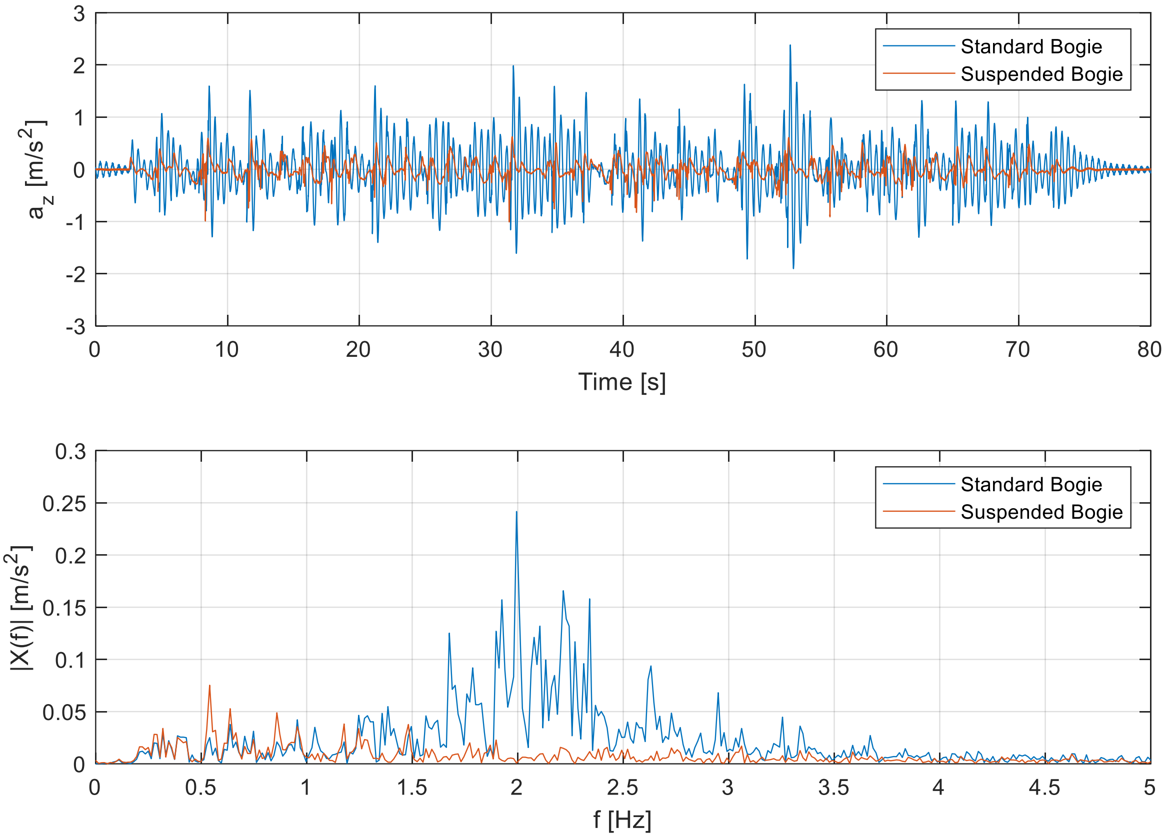

Figure 6. Vertical accelerations of the front carriage at the Skogforsk test track driving with 1.8 km/h

While driving a forwarder over rough terrain, especially rolling movements are uncomfortable for a driver. Evaluating this, the roll angle speed in time- and frequency-domain is chosen based on [12]. The suspended bogie with its used tuning of the hydraulic circuit shows almost the same behaviour as the standard system. During maximum peaks of roll angel speed, compare t = 12 s and t = 57 s at Figure 7, the suspended bogie system has a slightly higher speed, resulting in a minor increase in roll angle. Taking the frequency domain of the roll angle speed in account, see Figure 7, both systems have their main frequencies around 0.25 Hz and 0.7 Hz. Considering this, there is no improvement in roll angle speed with the suspended bogie axle at low frequencies, in contrast to an advantageous behaviour regarding vertical accelerations at higher frequencies. The effect is based on the cross-connection of the left and right hydraulic cylinder, compare Figure 3. If one cylinder is moving at low speed, e.g. the left cylinder retracts, there is an oil-flow towards the rod chamber of the right cylinder, resulting in a retracting motion of the latter. These simulation results for the suspended bogie axle can be compared to a six-wheeled pendulum arm forwarder, which driving over the same test track at same speed [8]. With the concept presented in [8], maximum roll angle could be decreased only slightly, which is due to the low-frequency excitation.

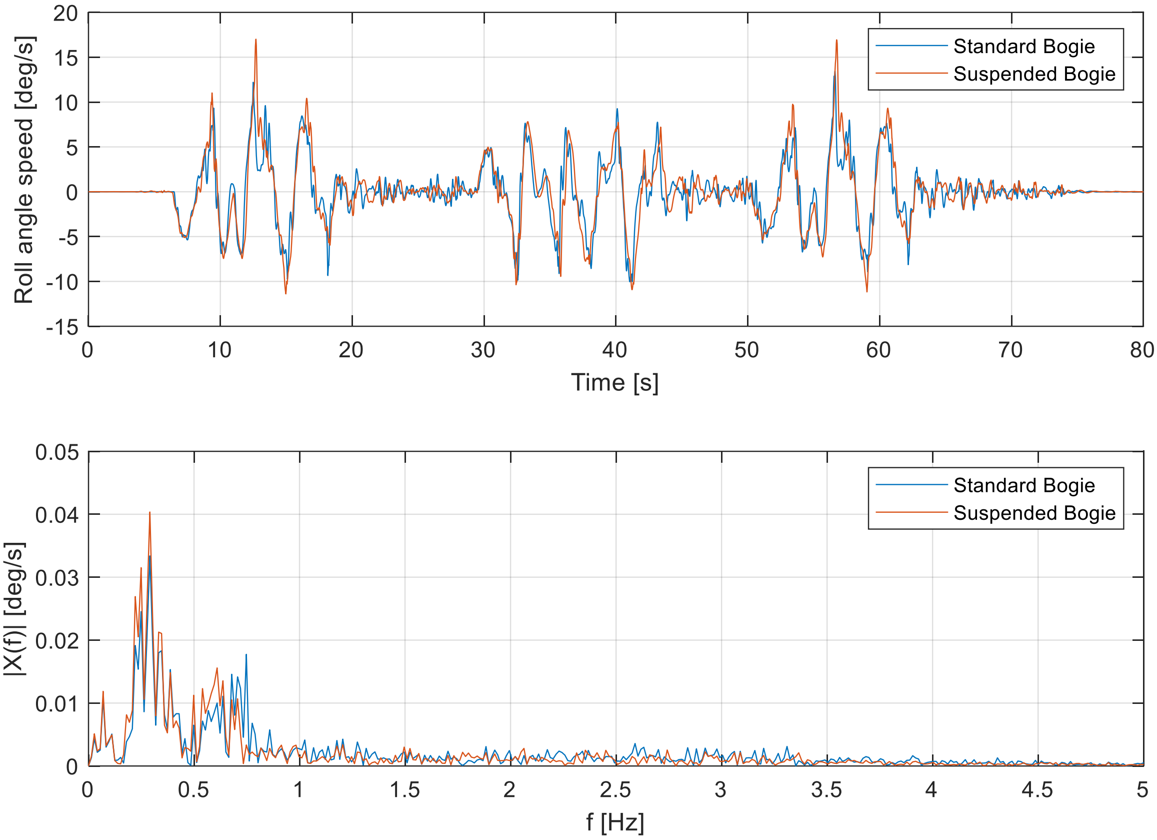

Figure 7. Roll angle speed at the Skogforsk test track driving with 1.8 km/h

4.2. Driving over a forest Road with 15 km/h

Driving loaded from the skid road to the landing area and unloaded reverse has a high proportion of time especially for long hauling distances. A test track which is supposed to be similar to a forest road is derived by downscaling the Skogforsk test track in vertical altitude with a factor of 6. This track is run over by both machine models at a vehicle velocity of 15 km/h. An advantage of the hydro-pneumatic suspended bogie axle while driving on forest roads with high speed is that wheel forces as well as vibrations are reduced.

As on the skid road, dynamic wheel forces are minimized significantly with the presented concept, compare Figure 8. Although only visualized for the front wheel of the front bogies in figure 8, the effect can be observed for each wheel. Another difference between both concepts is the varying damping behaviour after leaving the bumpy forest road, see the interval between 10 s to 14 s at Figure 8 and Figure 9. While the machine with standard bogie axles is still pitching and rolling, both motions are damped fast by the hydro-pneumatic suspension.

Furthermore, the amplitude of vertical accelerations is noticeable lower compared to a forwarder with standard bogie axles, see Figure 9. This results from the individual movement of each wheel, similar to a single-wheel suspension in the passenger vehicle sector. The frequency spectrum shows a clear peak at 2 Hz and a band between 2.3 Hz and 2.8 Hz for the standard bogie, whereby it has certain similarities with the frequency spectrum shown in Figure 6 for the Skogforsk test track. Nevertheless, a shift towards higher frequencies can be observed.

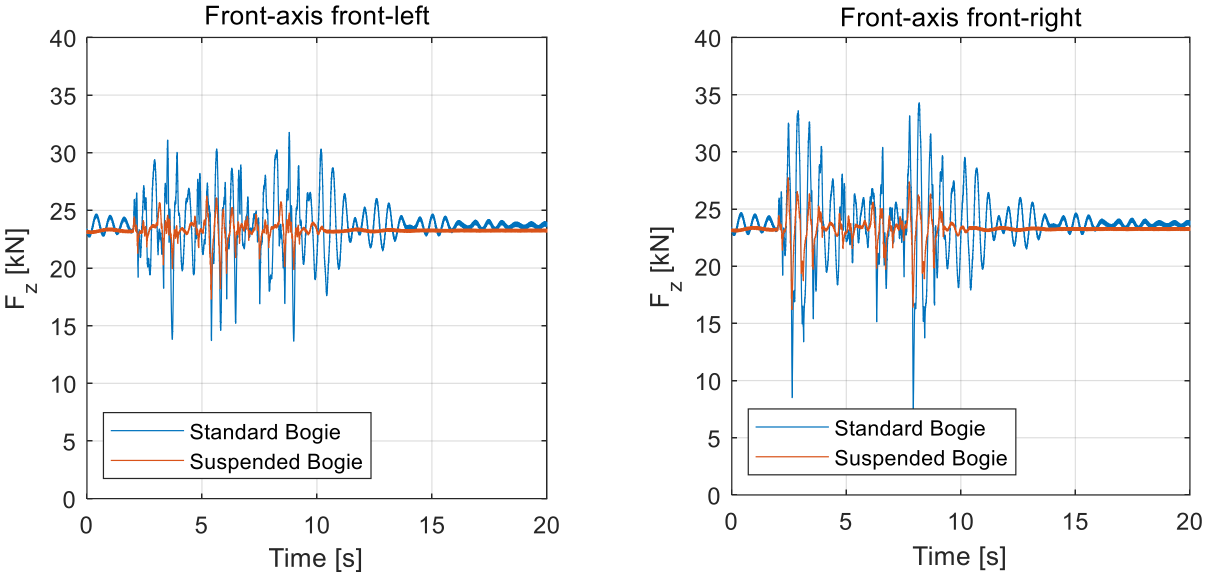

Figure 8. Wheel forces at a forest road driving with 15 km/h

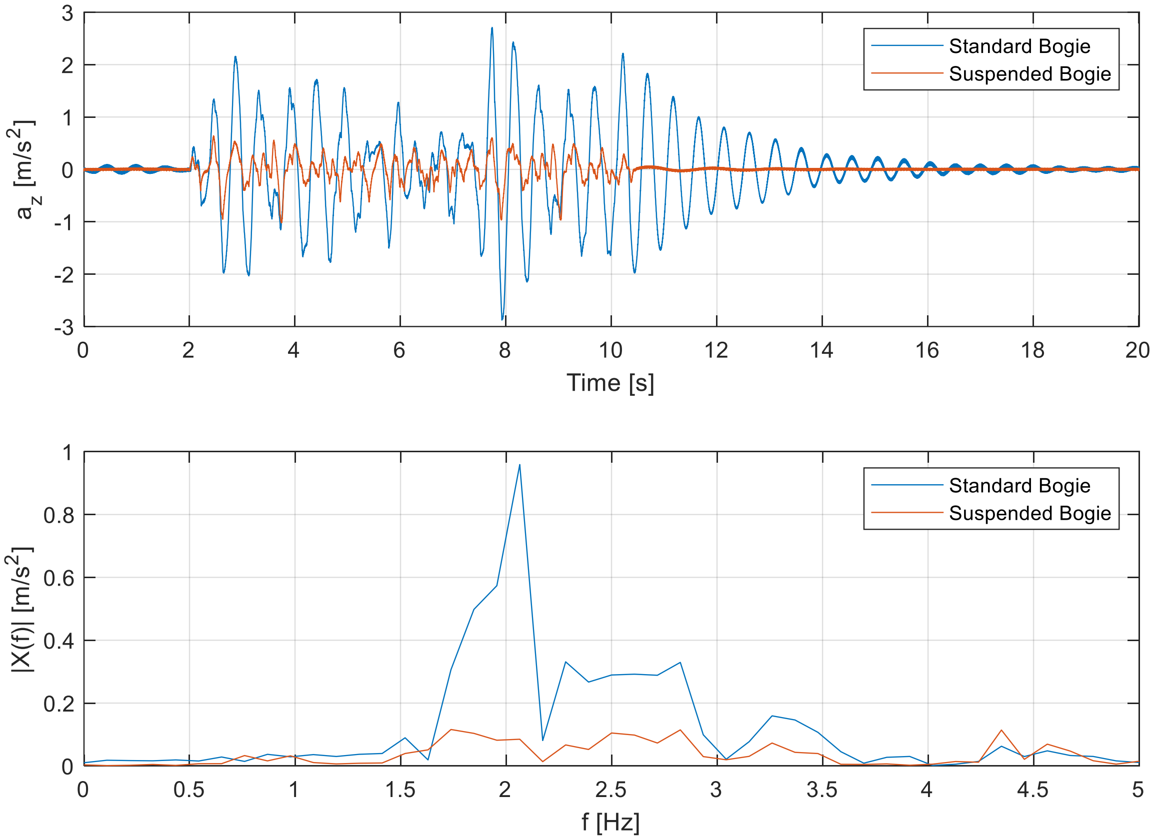

Figure 9. Vertical accelerations of the front carriage at a forest road driving with 15 km/h

In Figure 10, roll angle speed is compared. In difference to Figure 7, where the obstacles were higher, the maximum amplitude is obviously lower. While driving at the forest road, a suspended machine is rolling less then a standard forwarder, resulting in lower maximum amplitudes of the roll angle speed, compare Figure 10 for example at 3.2 s. In this case, main frequencies of roll angle speed varies in the range of 1.8 Hz to 3 Hz, significantly higher compared to the application scenario during driving on a skid road. Due to the higher vehicle velocity, a transfer towards higher frequencies is logical. Under these driving conditions, a reduction of the maximal roll angle speeds up to 35 % is possible with suspended bogie axles. Obviously, suspension systems show higher effects when impinged with higher-frequency excitations.

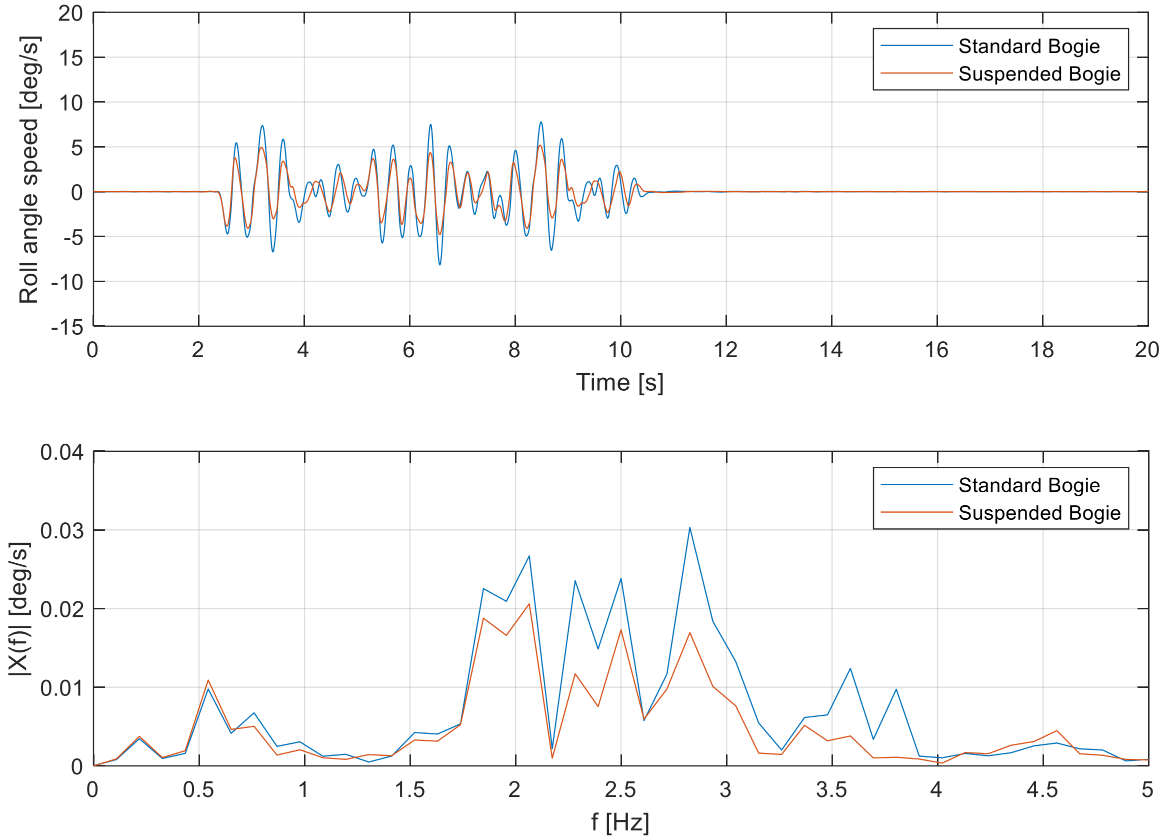

Figure 10. Roll angle speed a forest road driving with 15 km/h

5. CONCLUSION

Regarding the requirements of today’s forestry machines, in this paper a hydro-pneumatic suspended bogie axle for a forwarder has been tested simulative and compared to a standard bogie axle for driving conditions on a skid road and a forest road. Therefore, a model of a forwarder with standard bogie axles was built and validated. Based on this, an additional model of a machine with hydro-pneumatic suspended bogie axles was set up and the functionality of the suspended system explained. Dynamic wheel loads can be decreased up to 40 % with the new concept in both cases. Furthermore, accelerations in vertical direction are reduced to one-third compared to an in-market machine. Evaluating this result not only in time domain but also in frequency domain shows no significant Eigen frequencies of a machine with suspended axles. Roll angle speed of a suspended machine is decreased while driving fast on a forest road.

Summarizing, a forwarder with hydro-pneumatic suspended bogie axles leads to a more sustainable logging process in relation to ground pressures, rut formation and driver’s comfort. Especially the significantly reduced exposure of the machine operator to accelerations in a harmful frequency range improve working conditions.

6. OUTLOOK

A crucial advantage of the presented suspension system is, in contrast to other mentioned suspension possibilities, the option to use bogie tracks for wet surfaces. Blocking the hydraulic cylinder, the behaviour of a standard bogie axle can be achieved. Therefore, a forwarder with this hydro-pneumatic suspension can be used under varying operational conditions.

The presented suspension system is a passive concept. With an active suspension, the ability to reduce accelerations and roll angle speed especially during low-frequent excitations can be improved. In addition, different test tracks can be investigated to evaluate the best parameter set for a specific machine and their working conditions. Furthermore, building-up a prototype machine with these hydro-pneumatic suspended axles would allow a validation of the expected effects shown with the simulation results.

7. ACKNOWLEDGEMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727883.

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