# MULTI-OBJECTIVE PERFORMANCE OPTIMIZATION OF PENDULUM-ARM SUSPENSIONS FOR FORESTRY MACHINES

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## Abstract

The development of forestry machines is currently heading towards new solutions that reduce their impact on the environment and in particular on the soft forest soil. In addition, new machine solutions must be physically and mentally less damaging to the operators. Chassis-suspended solutions in the market of forestry machines are practically non-existent. The implementation of chassis suspensions in forestry machines is therefore a very interesting research area in forestry technology. In this context, the XT28, a six-wheeled medium size forwarder prototype with active pendulum arm suspension, is currently being realized by Extractor AB in collaboration with the Forestry Research Institute of Sweden. The present project focuses on analyzing and comparing the performance that active, semi-active and passive suspension systems with a pendulum arm architecture would provide to forestry machines, by studying their implementation in the XT28 prototype A methodology to optimize and analyse forestry vehicle suspension performance using multi-objective optimization algorithms, multi-body dynamics and standardized vibration measures is proposed and applied to the XT28 case. The proposed methodology provides a fair and standardized way to compare the performance of the different suspensions. Simulation and optimization results show that well designed pendulum arm suspension systems have the potential to significantly improve forestry vehicle performance in terms of terrain friendliness and whole body vibration levels, compared to unsuspended systems.

**Keywords:** chassis suspension, forestry machine, hydraulic suspension system, multibody dynamics simulation, off-road, rough terrain

## 1 Introduction

Development of forestry machines currently heads towards new solutions that reduce their impact on soft forest terrain, e.g. [1][2]. In addition, new machines must be considerably less damaging to the operators. Directive 2002/44/EC of the European Parliament and the Council of the EU limits the daily exposure of operators to whole body vibrations. Cabin and seat suspensions are usually used for reducing vibrations, but they are only effective up to a certain degree, due to their relatively short stroke length and directional limitations [3]. To develop forestry machines that are gentle to operators and terrain, it is essential to develop and implement efficient and robust chassis suspension solutions. Multiple wheeled tracks and bogies are current solutions that improve dynamic performance and ground contact area of forestry machines, but they do not include high-performing suspension elements.

The suspension of a vehicle has a decisive effect on its dynamic behaviour, and therefore on its comfort and ride performance and on its safety. According to Taghirad and Esmailzadeh [4], performance requirements for a suspension conflict with each other, making it impossible to design a suspension system that is optimal in all aspect, i.e. there must be a trade-off between several important requirements. Conventional passive systems, consisting of spring-damper combinations, although simple, effective and inexpensive, clearly limit the possibilities to simultaneously fulfill the design requirements. Active and semi-active suspensions have been studied for a long time. These systems offer a degree of adaptability, which improves the possibilities to do design trade-offs. Active suspensions use an actuator, usually hydraulic or pneumatic, which can include parallel passive suspension elements. A series of sensors measure the instantaneous state of the vehicle, the data is processed by a CPU and an appropriate control signal is sent to the actuation system. The cylinder provides the desired force, limited in response time and magnitude by the hydraulic, pneumatic or electrical system that actuates it. An additional advantage of an active system is that it can sometimes provide levelling or height adjustment of the vehicle. Semi-active suspensions are based on the use of a spring in parallel with a variable damper, which allows adjustment of its damping coefficient. A characteristic disadvantage of semi-active suspensions relative to active suspensions is that they can't add energy to the system, but only change the rate of energy dissipation. Despite this there are some advantages of a semi-active system over an active one, such as significantly lower cost, power consumption, less complexity, and consequently a simpler design [5].

An effective way to approach suspension design is as an optimization problem, in which a series of performance indices coupled with evaluation criteria define an objective function, and for given operating conditions the optimal set of design variable values that minimizes (or maximizes) the objective function must be found. In other words, a search for the suspension design variable values that result in the "best" possible performance of the system.

Skogforsk, the Forestry Research Institute of Sweden, is the central research body of the Swedish forestry sector. Among a wide range of areas, Skogforsk conducts forestry technology and machinery research in collaboration with leading machinery manufacturers. Within the framework of this research a forwarder prototype with an active suspension, the XT28, is currently being developed to evaluate vibration and ground damage reduction through suspension systems. The prototype's suspension consists of an independent hydraulically actuated pendulum arm system which, with the implementation of an effective active suspension control system, has the potential to significantly improve riding conditions as investigated in previous projects at KTH Royal Institute of Technology and Skogforsk, e.g., [6][7]. A CAD conceptual representation of the full-scale prototype machine is shown in Figure 1.

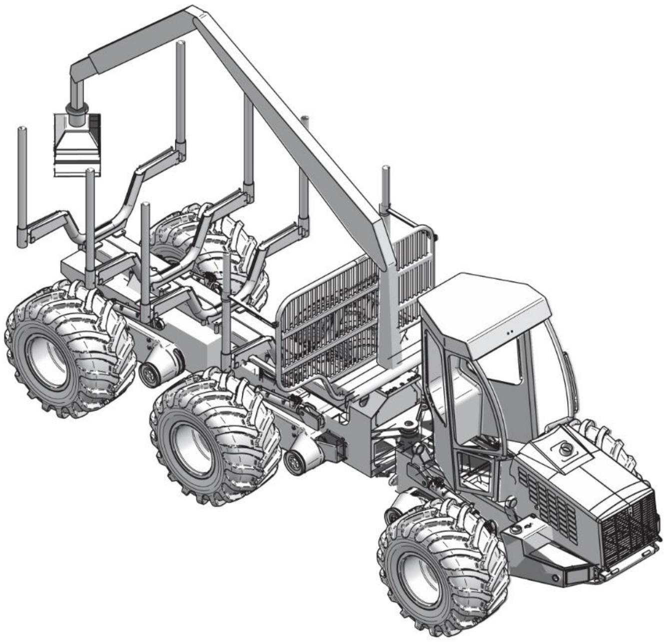

*Figure 1. The XT28 forwarder prototype, from [8]*

The main purpose for the research presented in this paper was to propose a model-based methodology to automate design optimization of forestry machine suspensions with the use of optimization algorithms and multi-body dynamics (MBD) simulation software. The second challenge was to apply the proposed methodology and to optimize active and semi-active control systems, as well as a passive system, for the XT28's pendulum arm suspension, and to compare the performance of the different solutions. The remainder of the paper is organized as follows: first the optimization process and performance evaluation methodology is elaborated on, then optimization results for the XT28 suspension systems are presented, and finally the work is discussed, conclusions are made, and further work is proposed.

## 2. Optimization process and performance evaluation

As previously discussed, the two main performance concerns for forestry machines are currently whole body vibration health effects and terrain damage. The design objectives of the suspension will therefore be focused on

- reducing accelerations of the vehicle's sprung mass and principally their effects on the operator's health, and
- minimizing the amplitude of dynamic tire-ground loads, thus maximizing terrain-friendliness and ride safety.

Consequently, the performance indices extracted from simulations will be accelerations in vertical, longitudinal, and lateral directions in the operator seat and normal tire-ground dynamic forces in each of the machine wheel-ground interfaces. A way to evaluate these performance indices must be specified, since it doesn't make sense to use these values directly. In the first place, the sum of the RMS values of normal tire-ground dynamic forces in each of the tires will be used to assess the impact on the terrain:

$$N_t = \sum_{j=1}^{n} \left[\frac{1}{T}\int_0^T N_j^2(t)\,dt\right]^{\frac{1}{2}} \tag{1}$$

With $T$ being the measurement time and $N_j(t)$ the measured dynamic tire-ground normal force for each of the $n$ wheels (in the case of the XT28, $n$=6) as a function of time.

Ride quality will be evaluated as recommended by the ISO 2631 standard [9], using frequency weighted values of the measured accelerations and taking directional weighting factors into account. The total value of the weighted RMS acceleration will be used as a function to minimize, defined by

$$a_v = \left(k_x^2\, a_{wx}^2 + k_y^2\, a_{wy}^2 + k_z^2\, a_{wz}^2\right)^{\frac{1}{2}} \tag{2}$$

Where $k_{x,y,z}$ are directional weighting factors (for evaluating the health effect of full body vibrations in seated persons $k_x$=$k_y$=1,4; $k_z$=1) and $a_{w\,x,y,z}$ is the weighted RMS acceleration value in each Cartesian direction:

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2(t)\,dt\right]^{\frac{1}{2}} \tag{3}$$

Where $a_w(t)$ is the weighted acceleration as a function of time in a certain direction (See ISO 2631) and $T$ is the duration of the measurement.

Additionally, the vibration dose value (*VDV*) will be calculated in each Cartesian direction:

$$VDV = \left[\int_0^T a_w^4(t)\,dt\right]^{\frac{1}{4}} \tag{4}$$

The maximum of the directional VDV values will also be used in the final evaluation of ride comfort performance, but not as an objective in the optimization problem.

Finally, the two dimensional objective function to minimize in the multi-objective optimization problem is defined as

$$OBJ(x) = [a_v\,, N_t] \tag{5}$$

With $x=[x_1,\ldots,x_m]$ being a vector corresponding to the set of $m$ design variables that define the suspension system.

To solve the defined optimization problem, our proposal is to use a multi-objective genetic optimization algorithm. There are several reasons for using a genetic algorithm GA. Principally, GAs present no restrictive requirements for the objective function and they don't need any information apart from the function evaluation results. In the present problem, the objective function depends on the simulation model, which can be highly complex, nonlinear and discontinuous. Additionally, the GA is suitable in initial design stages where there are many design variables to manipulate with quite unrestricted ranges, and it's highly reliable in finding global optima [10]. Also, the suspension design problem presents trade-offs among different design objectives. To solve a problem with these characteristics, an evolutionary multi-objective optimization (EMO) algorithm is appropriate [11]. The result of the optimization procedure will therefore be a set of Pareto-optimal solutions, which provides much more information about the suspension's capabilities than a single point optimal result. Figure 2 shows a scheme of the proposed optimization process.

The multi-body dynamics simulation software MSC Adams [12] will be used for 3D full machine dynamic modelling. The model will be used to simulate the dynamic machine behaviour under certain conditions when equipped with a given suspension system. The suspension and its control will be modelled separately using the model-based design tool Simulink [13] and the coupled problem will be co-simulated. The tire-ground interaction is also modelled as an a sub-model. This modular model structure allows the implementation of different suspension and control systems without the need of modifying the machine model, as well as an easy change of user defined tire models and road excitations. For the optimization procedure, a simple point contact tire model will be used, but for the final evaluation of the performance of the optimized solutions, the wheel-ground model FTire [14] will be used- FTire has previously been shown to give realistic dynamic responses for machines operating on very rough terrain [15]. The input data for these simulations will be specific values for the suspension design variables, and the output data will be the performance indices. The scripting program Matlab [16] will run the optimization algorithm and control the whole process. From each simulation in the optimization process, the optimization algorithm transforms the simulation output data to objective function values and decides on a new set of values for the design variables. A new simulation is the executed with the new values and this process continues until one of the stopping criteria of the algorithm is satisfied.

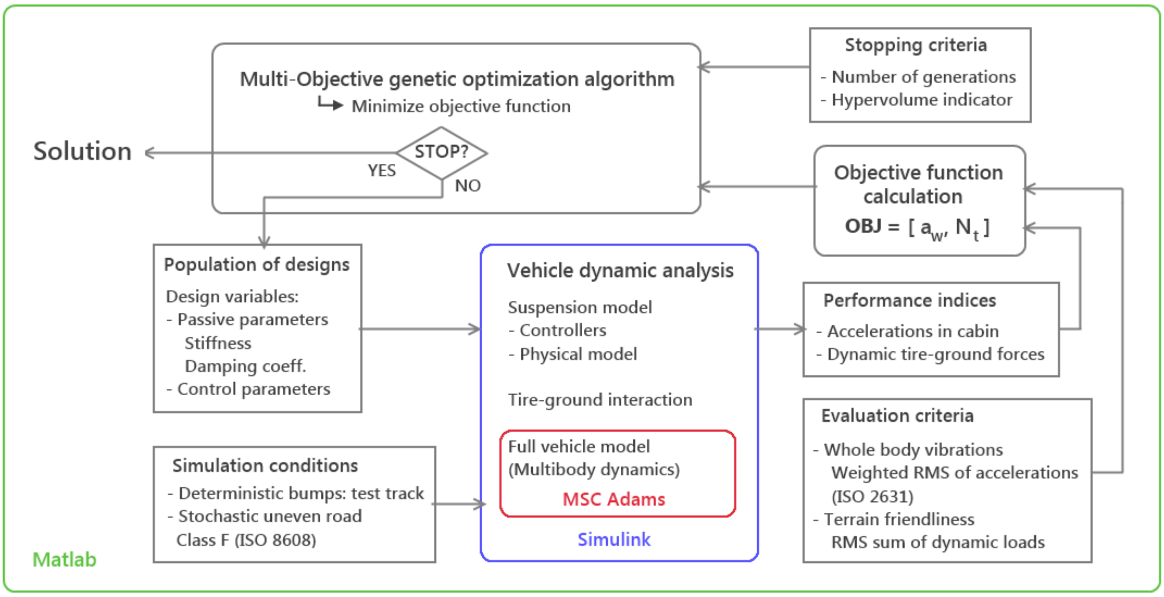


*Figure 2. Optimization process schematic representation*

Since the behaviour of the suspensions can vary, depending on the conditions, it is of high interest to analyze their performance with different types of ground profiles. For the dynamic machine analysis, two types of representative ground excitations are used. In the first representation, a part of the profile of an existing hard ground test track used by Skogforsk for standardized vibration evaluations [17], see Figure 3, is used. Secondly, a stochastic uneven terrain with a certain road classification according to the ISO 8608 standard [18] is used. In the ISO standard, a PSD is considered representative of forest terrain roughness

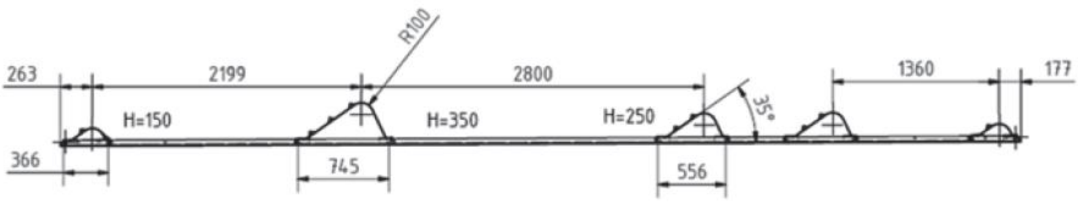


*Figure 3. Portion of Skogforsk's hard ground test track*

Oh et al. [19] and Pazooki et al. [20] estimated the PSD of soft forest terrain from measurements in the forest soil. The approximated PSD curves when compared to the ISO classes are similar to those of a road of ISO class 'F' in the relevant frequencies [8]. The use of a PSD curve corresponding to an ISO road class 'F' is therefore recommended for the synthesis of an uneven forest terrain profile.

In terms of travel speed and carried load, the simulation conditions should be adapted to the specifications of the vehicle. In the case of the XT28, the specifications state a mean speed of 6 km/h on forest ground. For riding on the Skogforsk test track, 0.5 m/s is the standard speed. A payload is not specified at the time of this study, but 10 tons, i.e. 70% of the loading capacity, will be considered. For simplicity, a constant velocity and a straight traveling path will be used, which make it easier to replicate the results.

## 3. Results

### *3.1. Optimization results*

Figure 4 shows the final Pareto-optimal solution fronts of the passive, active and semi-active suspension systems for both the hard ground test track and the stochastic uneven terrain excitations. For both cases, the performance of the active system is better than that of the semi-active, which in turn performs better than the passive one. This is more accentuated in the hard ground test track excitation case.

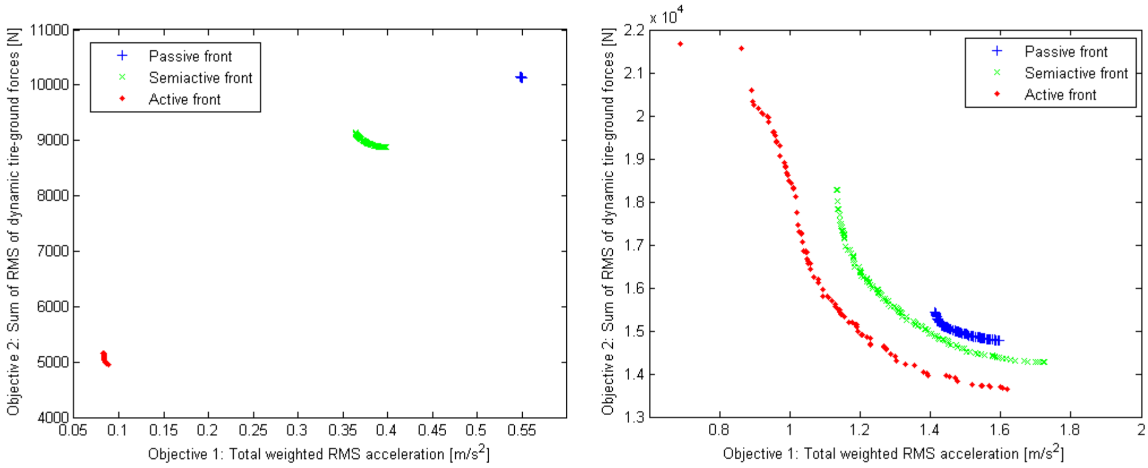


*Figure 4. Pareto-optimal fronts of the suspensions for Test track and (left) Stochastic terrain (right)*

Two different strategies were considered for control of the active and semi-active systems, namely EGH and L-EGH control. EGH is a control strategy which attempts to reduce the independent contribution of each of the six ground contact modules to dynamic tire-ground loads and vibration of the sprung mass. L-EGH combines the previous strategy with a level controller, with the objective to reduce pitch and roll motions. Figure 5 shows a comparison of the optimal fronts from optimizations with each of the control systems. The latter performed better in every aspect, except for dynamic tire-ground forces in the semi-active suspension case with the hard ground test track ground excitation. The difference in performance of the control strategies was much more significant in the case of the optimizations with the test track, in which the pitch and roll motions of the forwarder are more significant. In genera,l the L-EGH controlled suspensions offer a better overall performance than the EGH controlled..

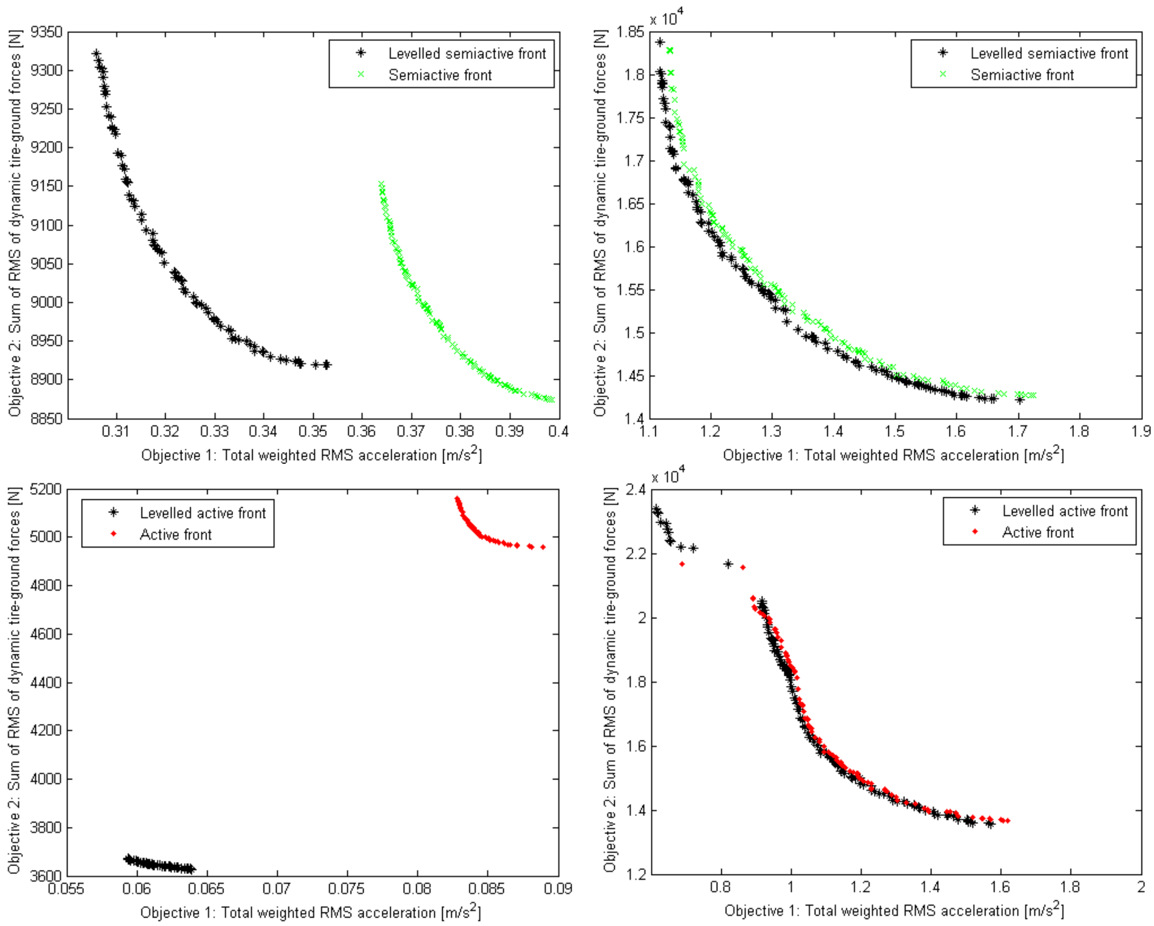


*Figure 5. Comparison of EGH and L-EGH control for Test track (left) and Stochastic terrain (right)*

*3.2. Simulation with FTire*

After the optimization runs, a solution from the Pareto-optimal fronts from each of the three cases: passive and L-EGH controlled semi-active system and active system, were chosen. The solutions correspond to the ones with median fitness values, i.e., the ones in the middle of the front. The three solutions were simulated using the FTire model. It must be mentioned that the initially selected active solution, which was optimal when simulated with the simple tire model, was unstable when simulated with the FTire model. The XT28 tipped over due to excessively wide roll movements caused by lack of stiffness in the suspension. The stiffness was therefore manually increased in order to obtain a stable solution. Apart from these three solutions, an unsuspended version of the machine was simulated, which was achieved by changing the rotational joints between pendulum arms and chassis to fixed joints, leaving the machine with a structure similar to that of fixed axle machines.

The performance of the systems in terms of the RMS sum of dynamic tire-ground forces, total value of weighted RMS acceleration, and Vibration Dose Value (VDV), is presented in Table 1. The percentage values correspond to the reduction relative to an unsuspended case. The VDV is also given as an extension to a standardized working period of 8 hours. It can be seen in the table that the reduction of dynamic tire-ground loads and whole body vibrations in all cases is at least 50% relative to the unsuspended machine, according to the evaluation criteria. In the case of VDV, as discussed before, EU Directive 2002/44/EC imposes limit and action values of 21 and 9.1 $m/s^2$, respectively. If the test track was an appropriate representation of a continuous forwarder operation, the unsuspended machine would not comply with the directive, implementation of the passive or semi-active suspension systems would result in VDV values safely below the limit value, but above the action value. The only suspension system that would provide complete compliance with the directive would be the actively controlled one.

*Table 1. Results of the simulation with FTire*

| | $N_t$ $[kN]$ | $a_v$ $[m/s^2]$ | VDV $[m/s^{1.75}]$ |
|---|---|---|---|
| **Unsuspended** | 42.378 | 3.312 | 7.905<br>8 hours: 44.002 |
| **Passive** | 17.370<br>(-%59.01) | 0.766<br>(-%76.87) | 1.776<br>(-%77.53)<br>8 hours: 9.886 |
| **Semi-active** | 17.610<br>(-%58.45) | 0.781<br>(-%76.42) | 1.692<br>(-%78.60)<br>8 hours: 9.418 |
| **Active** | 13.339<br>(-%68.52) | 0.590<br>(-%82.18) | 1.610<br>(-%79.63)<br>8 hours: 8.961 |

## 4. Discussion

Forest machines with active, semi-active and passive suspension systems can present great performance advantages over unsuspended machines, both in terms of terrain friendliness and reduction of whole body vibrations. In particular, the results indicate that forestry machines with active suspension such as the XT28 have the potential to minimize dynamic tire-ground forces and sprung mass vibrations in a way that isn't possible with other systems. This has special significance in situations where the terrain irregularities cause differences in vertical wheel positions of relatively high amplitude as in the case of the test track bumps. Apart from the obvious advantages, this supposes an ability to operate in more difficult conditions than usual, or at a higher speed, which would improve productivity.

The proposed optimization methodology was effective and efficient in obtaining optimal sets of design variable values for a given simulation model. The difference between the different suspension systems' performance in the optimization procedure and when simulated with the FTire model varies significantly, as can be seen in Table 1. This raises questions to the compatibility of optimization results using such a simple tire model with more realistic conditions. Although simulation models always can be improved, the proposed methodology or variations seems reasonable for further development. In particular, the use of a multi-objective optimization algorithm fits perfectly to the suspension design task, being a highly iterative process that presents a trade-off between different design objectives.

The performance of active and semi-active systems highly depends on their control system, and the design of control systems that consider full vehicle states can present a better performance than the use of simpler strategies. In particular, reduction of pitch and roll motions pays an important role both in the reduction of whole body vibrations and tire-ground dynamic forces, mainly when the vehicle has a high centre of mass. Additionally, when designing a control system it is important to assure a good robustness in all situations, since the system's behaviour can highly vary when subjected to different conditions.

A single point vertical tire contact model doesn't seem appropriate to obtain optimization results that are relatable to reality when regarding uneven terrain or bumps/obstacles as terrain excitation. The use of simplified simulation models should always be accompanied by verification and validation, and their limitations considered when analyzing the results.

## 5. Conclusions

A model-based and simulation-driven methodology for designing, optimizing and assessing and chassis suspensions for off-road working machines operating on rough terrain is proposed. The core model is a dynamic multi-body systems model that is co-simulated with a suspension control model, and a tire-ground interaction sub-model. Multi-objective optimal solutions for tire-ground forces and operator exposure to vibrations are the searched for with a genetic algorithm and presented as Pareto-optimal solutions. The solution that corresponds to the one in the middle of the Pareto-optimal front is then verified with dynamic simulations performed with a system model with the simplified tire-ground interaction model (Fiala) replaced with the much more detailed FTire model

The dynamic multi-body dynamic simulations are performed with the software MSC Adams. The suspension control algorithm is modelled in Simulink and the simplified tire-ground interaction model is an Adams sub-model. Two types of representative ground excitations are proposed: a part of the profile of a standardized test track, e.g. the Skogforsk hard ground test track, and a stochastic uneven terrain with a certain road classification according to the ISO 8608 standard. The multi-objective optimization problem to reduce the variation in the tire-ground contact forces and the operator whole body vibrations is performed with an evolutionary multi-objective optimization (EMO) genetic algorithm (GA) implemented in the tool Matlab.

The proposed suspension optimization methodology has been explained with and applied to the task to design three different pendulum arm suspension systems (a passive, s semi-active, and an active) to the full scale six-wheeled medium-sized forwarder prototype XT28. It can be seen in the table that the reduction of dynamic tire-ground loads and whole body vibrations in all cases is at least 50% relative to the unsuspended machine. If the test track was an appropriate representation of a typical forwarder operating on rough terrain, the unsuspended machine would not comply with the EU Directive 2002/44/EC, which imposes a limit value of 21 $m/s^2$, and an action value of and 9.1 $m/s^2$. Implementation of the passive or semi-active suspension systems would result in vibration dose values safely below the EU Directive 2002/44/EC imposed limit value, but above the imposed action value. The only suspension that showed a potential to provide complete compliance with the directive would be the actively controlled one.

## 6. Future work

The next step of realizing the pendulum arm suspended XT28 prototype is to detail, implement, and verify the active control system. The presented optimization methodology and simulation models are available to assist in that process.

In the future, XT28 tests with standardized vibration measurements will be performed on the Skogforsk test track. With test results and more information on the suspension system, the tire, suspension and vehicle models can be improved and adjusted in order to have simulation results that mimic the real behavior as close as required.

Very simplified approaches were taken to model the physical suspension systems and the tire-ground interaction for the optimization model. In the suspension system, springs, as well as passive and variable dampers were modelled as linear elements. The response of the variable damper and the active actuator was modelled as a first order system with a certain time constant. Springs, in general, and dampers, in particular, are far from linear, and active and semi-active system responses depend on the hydraulic/pneumatic/electrical system that actuates them, which could be modelled in more detail. It was also observed that a single-point vertical tire-ground contact model doesn't seem appropriate in uneven terrain or bumps/obstacle course conditions. It is therefore recommended for future work to improve suspension models and try other tire models with higher complexity but with low enough calculation times for their use in optimization procedures.

Furthermore, it would be interesting to try new simulation conditions by implementing soft soil terrain models, changing travel velocity of the machine and considering highly sloped terrains, in which the active system would show its levelling capabilities.

Finally, the suspended forwarder was simulated with the FTire tire-ground interaction model and its performance improvement over that of an unsuspended version of the machine was analysed. It would be interesting to repeat the comparison but with a version of the machine with bogies instead of a fixed axle equivalent, since it would be more representative of the current technological state-of-art for forestry machines.

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