Snowcat Undercarriage Suspension System: Key Factors To Optimize Performance

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Abstract—**This paper proposes the implementation of the skyhook control on snowcat undercarriage suspension using a digital twin to improve performance and reduce physical prototyping. The considered snow groomer is a tracked vehicle equipped with semi-active hydraulic suspension. First the identification of the key factors is carried out using a digital model which allows to compute the suspension response. This tool is based on a real time co-simulation between a Mevea multibody model of the vehicle and a MATLAB/Simulink control model. After the validation through field measurements, the traditional automotive skyhook control strategy is implemented aiming to increase the comfort by reducing the lower frequencies amplitude. The results of the optimal configuration will be presented and compared with the current suspension system response.**

Index Terms—**Snow groomer, digital model, skyhook, suspension, Digital Twin, simulation**

I. INTRODUCTION

The heavy duty industry has always been an extreme challenge for the entire automotive sector. The harsh environment conditions, the absence of infrastructures and the extensive working times have constantly pushed the manufactures to improve the quality as well as the comfort of their vehicles. Snow groomers, also known as snow cats, are part of this category and therefore such characteristics are essential for a successful product. More specifically, these machines are designed mainly to prepare all types of skiing slopes around the world. This complex task requires the snow cats drivers to groom many kilometers of slopes every night with all kind of snow type and weather. It is clear that to obtain the best result the operators have to work on a comfortable machine and part of this feature comes also from a well designed suspension system.

The goal of this project is to contribute to the development process of a more sophisticated suspension system for the Prinoth Leitwolf LT, see figure 2. To reach this objective, the first task is to model the current set-up in order to explore which are the key factors and components influencing more the system response. The subsequent step is to understand if any control solution, in this case the skyhook control, can be implemented and effectively benefit the vehicle comfort. The method chosen to test and validate the results is based on custom build digital model, which allows to further explore the recent concept of digital twin also on this type of machines.

Historically, the most common way to improve any product has been testing different solutions using a real prototype. This approach requires a lot of time and components to be produced, mounted and tested, which translates in a considerable cost for any company. For this reason, in the last years the concept of Digital Twin (DT) became really popular. Its first applications aimed to improve the developing process of a product by building a digital copy which could be virtually tested and improved, hence reducing the physical prototyping [1]. Nowadays the term DT is used in so many different applications fields that it doesn't have a univocal definition. Therefore, to define the simulation model built for the presented work, the categorization proposed by Kritzinger et al. will be adopted [2]. As represented in figure 1, DT is just an overarching class whereas a digital model is a sub-group which is essentially based on a physical object, a digital one and a non-automated connection. In this project the real life machine is the Prinoth Leitwolf LT, which will be modelled using a co-simulation between Mevea and Simulink, and validated using pre-recorded field measurements. From the many promising suspension control solution, it has been decided to test the automotive skyhook strategy. By analyzing the results it will be then decided if it is worth it to implement this set up also on a physical prototype.

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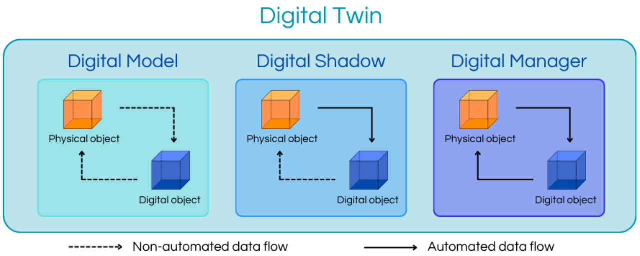


Fig. 1. Digital Twin classification.

II. MEVEA-SIMULINK CO-SIMULATION

Snow groomers are categorized as Off Highway Vehicles (OHV) and because their only purpose is to work on the snow and prepare the skiing slopes they are equipped with tracks, see figure 2. This is an essential feature which allows to better distribute its weight and avoids getting stuck, however it requires an uncommon undercarriage structure.

Fig. 2. Prinoth Leitwolf LT, image rights Prinoth AG.

A. Literature review

Generally, the snow groomers undercarriage architecture has always been really similar to the one of Armoured Tracked Vehicles (ATVs) like tanks, where each of the running wheels is attached to a torsional bar. This represents a simple durable solution that, even though it has been studied a lot, is still an interesting challenge in the simulation field. Nevertheless, the Leitwolf is a particular case since its suspension system is completely hydraulic. The main advantage of such a solution is the possibility for the driver to adjust the height of the vehicle which changes the contact area between the tracks and the snow, modifying consequently the grip and maneuverability of the vehicles. Its drawback, also due to how the running wheels are coupled, is the absence of literature and any relevant previous experiences. As mentioned in the introduction, the digital model represents the main tool for studying and improving the current machine suspension. In order to avoid starting from scratch, the decision was to continue to explore the potential of the Mevea-Simulink co-simulation which has already been implemented in previous applications by the Digital Twin Lab (DTL) of the Management Center Innsbruck (MCI) [3]. Co-simulations are not a novelty for car suspension studies, in fact some examples are dated back in the early 2000'. However, the Mevea-simulink connection has been explored only recently, a first example based on a forklift has been published in 2017 [4]. A part from the DTL experiences, the closest application to the one here discussed uses just a generated code from Simulink to model the hydraulic circuit and runs it inside the Mevea simulation [5], meaning many solutions can still be explored.

B. Physical object

As mentioned in the introduction, the digital object is a virtual representation of the actual physical one, hence before starting to improve the suspension system it is necessary to have a decent understanding of it. Figure 3 shows a side view of the undercarriage where it is clear to see that the track is kept in position by a rear sprocket, four running wheels and a front tensioning wheel. The sprocket and the front wheel are fixed to the frame while the four running wheels are part of the suspension system. In particular these are coupled in two pairs, each of them attached to a tandem that is indirectly connected to a hydraulic cylinder.

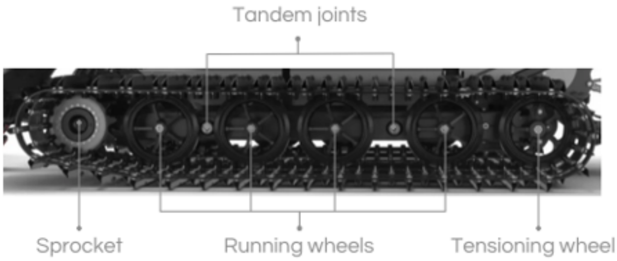


Fig. 3. Prinoth Leitwolf´s wheels lay out.

To better explain the kinematic chain, figure 4 reports the main components of just one quarter of the vehicle. From this vertical prospective it is possible to see that the tandem is connected via a revolute joint to a crank arm, which passes through the frame and is attached with the same type of joint to the cylinder. Such a configuration allows to control the vehicle height by increasing the pressure in the cylinder. To complete the suspension, two membrane accumulators are connected to each of the cylinders. During the operations phase the machine is raised at the chosen position and the hydraulic circuit behaves as a passive system. From this brief description is clear to see how much different this system is compared to the tradition torsional bars.

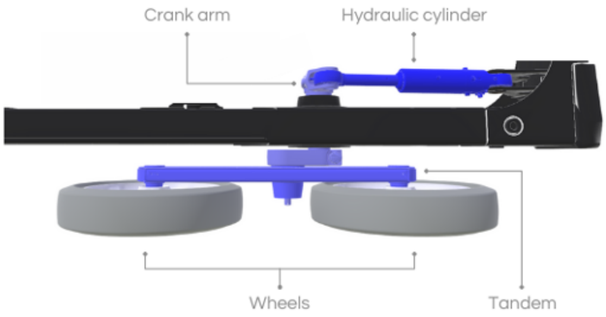


Fig. 4. Quarter suspension model of the Prinoth Leitwolf.

C. Digital object

Finally, the structure of the Leitwolf's virtual representation can be discussed. The main motivation behind the choice of continuing to explore the Mevea-Simulink co-simulation is the flexibility of the system. Mevea is a specialized multibody software which allows to reconstruct any object directly from CAD files as well as to model quite easily tracks and terrain. On the other hand Simulink is a popular and well known option for implementing any type of control strategies. These two tools can be connected via TCP/IP interface as shown in figure 5. Furthermore, this separation means that the multibody software is responsible for solving the differential equation while Simulink, by receiving the cylinder velocities, can compute the values of the forces and pass them back to Mevea. Last but not least, such a configuration allows also to run real-time simulations which are helpful to test new solutions.

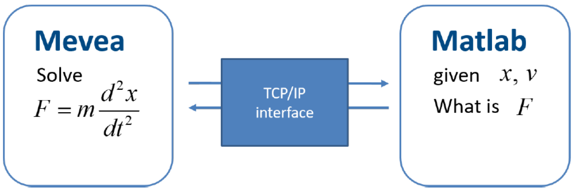


Fig. 5. Co-simulation connection type [3].

1) Mevea model: The multibody model of the machine has been assembled using only actual CAD files, which means that essentially all the vehicle geometries are as closes as possible to reality. For the undercarriage all the fundamental components have been added individually with their respective weights and moment of inertia. Since the remaining parts are rigidly fixed on the frame these have been added using larger assemblies, yet respecting the correct masses to not influence the actual weight distribution. Since the measurements have been recorded using a Leitwolf equipped with winch, blade and tiller these have also been added to the model. To match the test conditions, a terrain with similar characteristic to concrete and a rigid obstacle have been added to the model. These are decent approximations, however intuitively they are missing some real irregularities which will be evident in the validation phase. In figure 6 it is possible to see the Mevea multibody model of the Prinoth Leitwolf.

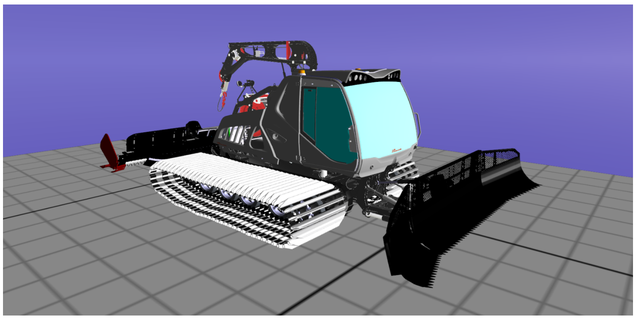


Fig. 6. Mevea multibody model of the Prinoth Leitwolf.

2) Simulink model: As already mentioned Simulink is in charge of controlling the multibody model. The connection between the two software is running with a time step of 1ms and is established using custom Simulink blocks created by the MCI's DTL. These blocks have to receive each of the cylinder velocities and send back to Mevea the respective force control signals. In order to calculate these values, each of the cylinder is modelled by reconstructing its hydraulic circuit (cylinder, accumulators and fittings) using the available Simscape components. To prove that the Simulink model would compute a realistic cylinder response, firstly many stand alone tests have been run. Since the results were satisfying, the complete co-simulation had then to been tested and validated.

III. DIGITAL MODEL VALIDATION

A key phase of the presented work has been the digital model validation. In fact, before implementing any solution to improve the current suspension system, it had to be proven that the co-simulation results are comparable to the field measurements. To fulfill this requirement, the validation has been based on data recorded during a specific test session. In particular, these machines are designed to move on snow but depending on the weather conditions its characteristics are constantly changing, representing an uncontrollable variable. To ensure the repeatably of the test and that measurements done in different moments are always comparable to each other, it has been chosen to mount rubber track on the machine and drive it on a concrete terrain. Finally to stimulate the suspension system, the Leitwolf had to drive over a small obstacle with a height of a few centimeters and a length similar the tandem dimension. Figure 7 reports both the real test set-up and the one in Mevea.

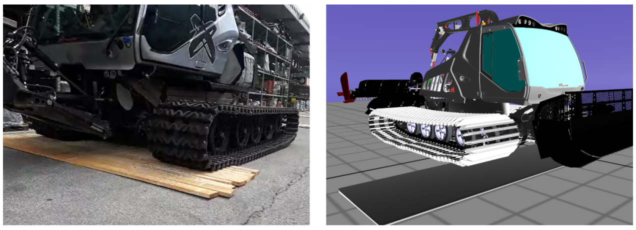


Fig. 7. Field test and simulation set up comparison.

It is now possible to discuss and analyze the co-simulation validation results. The data displayed in following graphs have been obtained with the machine driving at constant speed over the obstacle, stopping, reversing and driving again onto it. The most relevant values that have to be compared are the cylinders pressures and their position responses in the frequency domain. The cylinders absolute position will not be discussed as it is function of the pressure.

Starting with the front of the vehicle, figure 8 compares the normalized front cylinder pressures from the test field measurements and the simulation. In general the fitting is satisfying and misses only to reach the pressure peak during the first bump. This difference is likely related to the track modelling as it will be discussed later on. During the driving phases (before and after the hitting the obstacle) the model seems to be stiffer than the real machine. However it has to be considered that the simulation is perfectly controlling the vehicle speed and that the ground is completely flat. This idealizations are subsequently eliminating the external interferences and so their effects on the system response.

To confirm that the simulated front suspension is a decent representation of the real system it is possible to compare the cylinder position in the frequency domain. In figure 9 it is clear to see a good approximation, especially of the lower frequencies which are the one that the solution proposed in the next chapters is focusing on. Moreover, the peak related to the vibration caused by the track shape is also respected. A better fitting could have been obtained by running a longer field test and using a sampling frequency of 1 ms, however with the available data the result is satisfying.

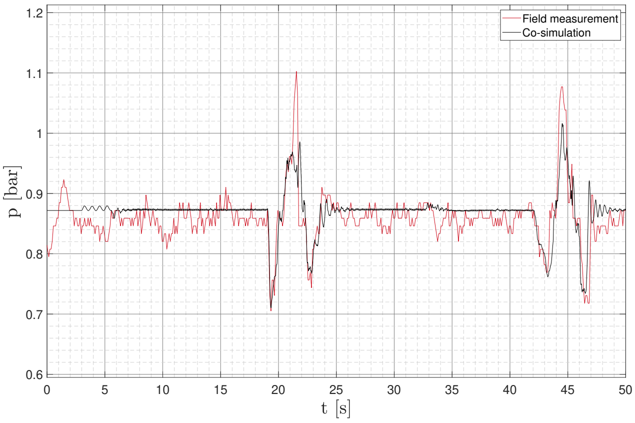


Fig. 8. Front left cylinder pressure comparison between measurement and simulation results.

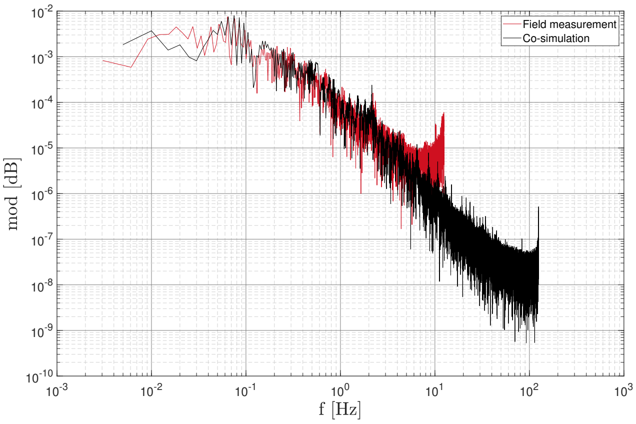


Fig. 9. Front left cylinder position comparison in the frequency domain.

After analyzing the front, at a first look the results of the rear suspension model seem to be not as good. Figure 10 shows that overall there is still a problem with the pressure peaks and in some cases the general course it is not completely correct (e.g. around the 21th second, which was also noticed for the front pressure). The first reason for this differences is that the two rear cylinder are controlled by the same pipe, where also the pressure sensor is located. This means that the recorded value is the result of the movement of the two cylinders, however for set up reasons just one position measurement is available. If the two rear tandem would hit the obstacle at the same moment there would be no problem, but even the smallest delay makes the visual comparison difficult.

The second reason for these differences is related to the track modelling. Since the front and the rear hydraulic circuits are almost identical, it is likely that some errors, e.g. the missing pressure peaks on the front, are caused by track simulation model. This is a

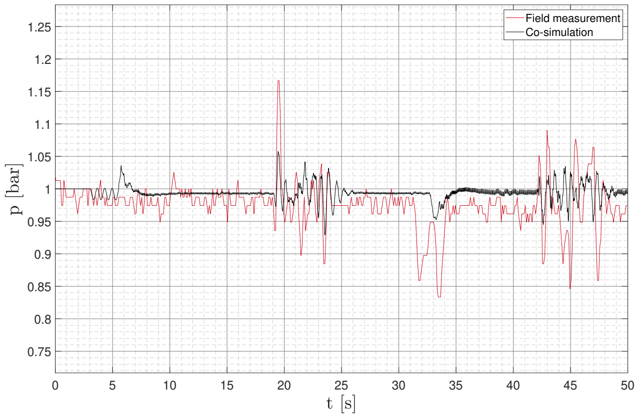


Fig. 10. Rear left cylinder pressure comparison between measurement and simulation results.

well known challenge in the ATVs field, therefore the chosen set up is a compromise obtained after many tests. Nevertheless, figure 11 shows still a satisfying fitting for the frequencies of interest, validating once again the co-simulation model.

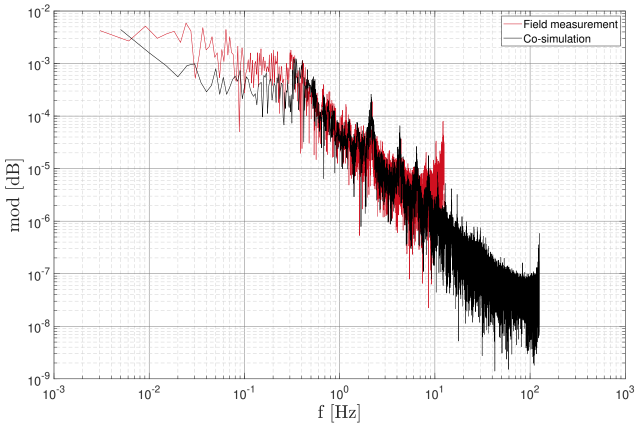


Fig. 11. Rear left cylinder position comparison in the frequency domain.

IV. VIBRATIONS IMPACT ON HUMAN BODY

The model validation tests have proven that the co-simulation approximates the reality at a satisfying level. From this result, it is possible to start implementing new solution to improve the suspension response. However, firstly it must be defined which frequencies have the most relevant impact on the driver comfort. This topic has been studied a lot trough the years with the goal of improving any type of ride, from traditional cars to heavy duty vehicles.

In general it is agreed that the comfort of the ride is mostly influenced by the low frequency vibrations. An often used classification states that the frequency band between 0.1 and 1 Hz is related to motion sickness. The main effects of this phenomenon is nausea and a general sickness feeling. The frequencies between 1 and 10 Hz are responsible for the Whole Body Vibrations (WBV). These are causing fatigue and sometimes can lead to internal body damage. Finally, over 10 Hz there are the Hand Transmitted Vibrations (HTV) which mostly cause damages to the hands [6]. The presented categorization is shown also in figure 12. These guidelines have been also validated by a survey which considered snowplow operators from 23 different U.S. states [7]. Despite not mounting tracks, these vehicles are used for similar tasks. From the study it is evident that vibrations, together with noise and limited visibility, are one of the major source for drivers fatigue. It appears to be clear that the whole body vibrations are the most critical ones. More specifically, it has been reported that monotonous low-frequency vibration around 3 Hz are strictly related this problem. As expected, the first modification suggested by the operators involved in the survey is to improve the vehicle suspension. Moreover, the proposed idea is to adapt truck suspension solution to the snowplows.

Since snow groomers are only a niche products, there are not specific studies about the topic. However, from this brief review it is evident that improving the comfort means reducing the low frequencies vibrations between 0.1 and 10 Hz. One of the suspension control strategies focusing on comfort is the skyhook control. In fact, has it will be evident in the next chapters, its effects will be limited to the low frequencies.

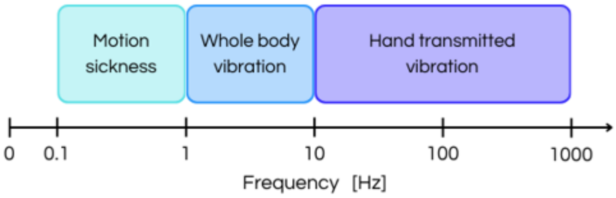
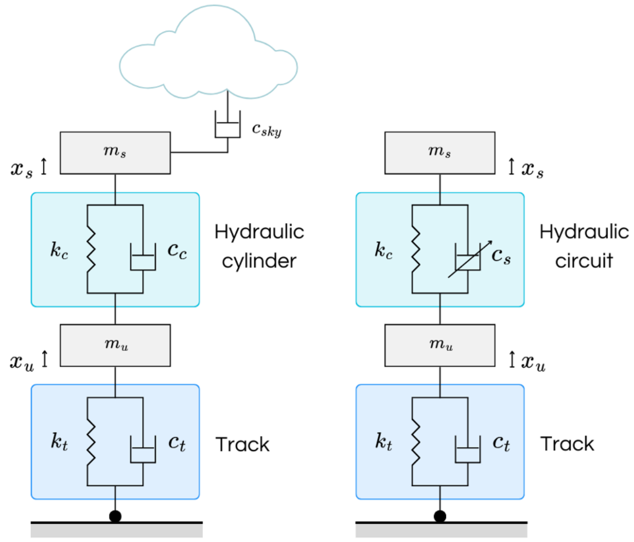


Fig. 12. Vibrations effect on the human body.

V. SKYHOOK CONTROL

The current Leitwolf hydraulic suspension set-up is an active system. In fact, to change the height of the machine, it is necessary to increase the oil pressure. However, during the driving phase the hydraulic circuits of the corners are usually closed. The vibrations caused by the terrain shape are therefore absorbed by a passive system. To improve the suspension response and increase the driver comfort, a solution worth it to be explored is the skyhook control. The advantage of this configuration is the possibility to electronically control its damping. This means that the system would become semi-active, as it would not be able to produce any additional force, but it can change the mechanical characteristic of the components.

The skyhook strategy is a well-known solution in the automotive industry. It has been firstly introduced in 1974, with the aim to improve the passengers comfort using a cost-effective configuration. During the years it has been tested a lot and generally the results are satisfying. For traditional cars, the increase of comfort has the downside of reducing the vehicle handling [8]. However, considering the large weight of a snow groomer and its relatively slow speed, this will not be a problem. Regarding heavy duty applications the first results have been produced around the 2000´s, for example with some applications in the agricultural field [9]. More specifically for tracked vehicles, some studies have been carried out on ATVs like tanks [10]. In all these cases, the simulations results proved a notable vibrations reduction. From the current available literature, the skyhook represents the perfect starting point to improve the current Leitwolf system.



a) Skyhook ideal principle b) Skyhook implementation

Fig. 13. Ideal and implemented skyhook control.

The basic idea behind the skyhook control can be explained using the quarter car model. This tool is commonly used in the car industry and, as the name says, it considers only one quarter of the vehicle. To further simplify the problem, the system is represented using a two degree of freedom model based on two masses, see figure 13. Respectively, m_s is the suspended mass and weights one quarter of the vehicle, while m_u is the unsprung mass and it includes the masses of the crank arm, the tandem and of the two running wheels. The hydraulic circuit, which acts as the suspension, can be modelled as the spring k_c set in parallel with the damper c_c. Also the track can be represented using a spring-damper system, this time characterized by k_t and c_t. The concept of the skyhook is illustrated in figure 13 (a), and ideally the suspended mass is connected via a damper to the sky. Such a configuration is impossible to reproduce in real life, however a similar result can be obtained by controlling electronically the damping value of the suspension, see figure 13 (b).

The remaining aspect that has to be introduced is how to choose the right damping value. There exist two types of skyhook strategies, the on-off version and the continuous one. Since this is the first attempt to introduce such a control, the simpler on-off skyhook has been chosen. This means that the system can switch only between two damping values, respectively c_{min} and c_{max}. The logic behind this approach is reported by the system 1. In other words, when the vertical velocity of the suspended mass as the same sign has the suspension deflection speed, the lower damping value is selected. In the opposite case, the maximum value will be adopted.

$$c_s = \begin{cases} c_{max} & \text{if} \quad \dot{x_s}(\dot{x_s} - \dot{x_u}) > 0 \\ c_{min} & \text{if} \quad \dot{x_s}(\dot{x_s} - \dot{x_u}) \leq 0 \end{cases} \qquad (1)$$

From a numerical point of view, the problem cannot be solved easily. In fact, for many automotive applications it is common to have access to valid reference data. However, for small production number machines with custom build suspension this is not the case. For the presented application it has been tried to fit a Simulink two degree of freedom model to the available measurements, in order to compute the numerical values of the parameters. Unfortunately, the result was not satisfying but such a task could be further investigated in the future to optimize the presented solution. Nevertheless, since the current set-up is quite simple, the best maximum damping configuration has been derived empirically.

VI. SKYHOOK IMPLEMENTATION

After introducing and motivating the reasons behind the choice of the on-off skyhook control, it is possible to discuss its implementation. Since for this application every parameter had to be computed empirically using various tests, the co-simulation had a fundamental role through out the process.

As explained before, the control uses the velocities of the two masses. In this case it means knowing the vertical velocities of the frame as well as the one of the attachment point between crank arm and tandem. To obtain this data, two virtual position sensor have been implemented in the multibody model. The real-time measurements are then send to the Simulink model, which derivatives and filters them. Obviously this approach cannot be used in a real implementation, nevertheless at this stage it represented the simplest way to understand if the skyhook would really improve the suspensions response. The next critical step has been calibrating the threshold value. It is well-known that in real application it is not possible to use zero as switching conditions. The sensors noise would in fact cause a continuous change of the damping value, that would impact the life expectancy of the electrohydraulic components. The best compromise between switching frequency and vibration reduction has been found after various tests. Deriving the right maximal damping condition required also a high number of iterations. In fact, increasing too much the damping provokes large undesired pressure drops. At the same time choosing a milder damping means a less significant suspension response improvement.

In the following the result of the best configuration, based on solenoid valves, will discussed. In order to have a decent set of data to compare the results with, the set up used during the validation phase has been maintained. In other words, the ground simulates a concrete soil and the machine has to slowly drive forth and back over the small obstacle. In figure 14 the pressure values from the front left cylinder are compared. As it is possible to see, the overall pressure curves is almost identical to the uncontrolled case. The main differences are some clearly notable spikes, which are caused by the sudden increase of the hydraulic circuit damping. Anyhow, these peaks do not represent any danger as they are still faraway from the system limits.

To evaluate the effectiveness of the skyhook, what really matters is obviously the vibration reduction. As displayed in figure 15, the normalized curves show an evident improvement exactly in the low frequency vibrations. That translates in a better driving quality. In particular, the most notable results are located around 0.5 Hz and close to 0.75 Hz, where the frequencies module are reduced even up to 30%.

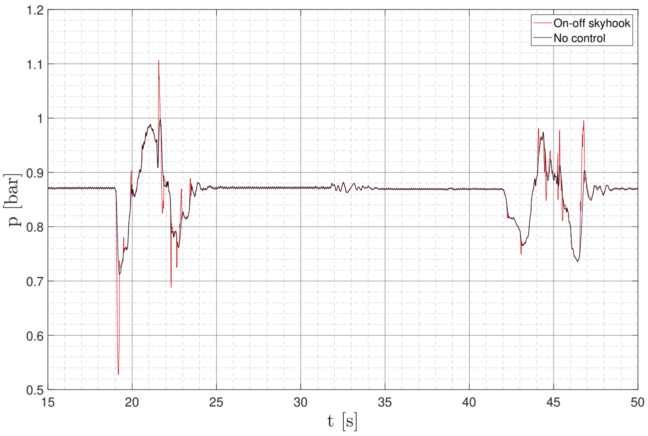


Fig. 14. Controlled and uncontrolled cylinder pressure comparison.

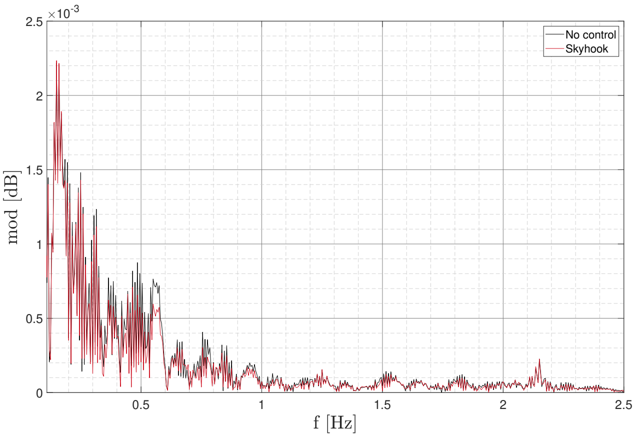


Fig. 15. Controlled and uncontrolled cylinder position, comparison in the frequency domain.

To complete the evaluation of the presented skyhook control application, a further test has been done using a soft snow terrain. In this case, instead of driving over a rigid object, the vehicle had to slowly drive forth and back on a small hill with the sides inclined at 10° and on ramp with a 15° angle.

Figure 16 shows the comparison between the result obtained with and without skyhook control. In this scenario, the same control used in the previous tests seems to not perform as good. As it is possible to see, the main difference is the reduction of really low frequencies peaks. In addition, between 0.4 and 0.5 Hz the spikes have been levelled. Anyway, the results of this test have been influenced by the robustness of the tracks. In fact, the soft snow has a dampening effect and at slow speed it becomes relevant. To increase the pitching effect it would be better to drive the vehicle at higher speed to induce larger accelerations. Unfortunately, the current track model does not perform correctly in this conditions and therefore these tests could not be run.

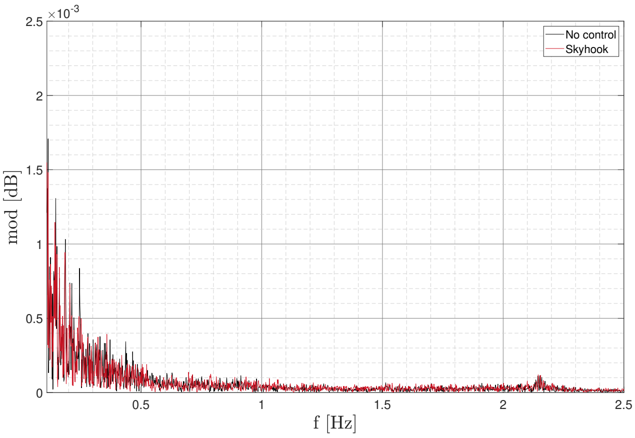


Fig. 16. Cylinder pressure comparison in the frequency domain.

VII. CONCLUSIONS AND FUTURE IMPROVEMENTS

The presented work aimed to better understand what are the key factors influencing a snow groomer hydraulic suspension response. Moreover, to increase the machine comfort, a possible implementation of the skyhook control has been proposed. To achieve these results, it has been decided to use a digital model. This tool allowed to further explore the effect of the tracks on the system. The presented co-simulation is also a valid contribution in the product development process. The flexibility of the model permits to first test any type of solution in the virtual environment and only after on the real machine. Hence, the traditional physical prototyping becomes essential just in the final stage, when it is necessary to compare the most promising alternatives.

Regarding the application of the on-off skyhook strategy in the digital model, it has been proven that it is possible to control the system by exploiting well-known strategies. Despite being a relatively simple solution, the skyhook results showed an evident reduction of the low frequency vibrations. Considering that the presented configuration has been developed to be also cost effective, the next step is to implement it on a real machine.

In the future, the first important improvement that could be done is to increase the multibody model robustness. Defining the track as well as the terrain characteristics is known to be a difficult task. However, by investing some resources, the co-simulation would become a universal tool where any type of modification could be tested in various conditions. Another useful step would be to successfully fit the two degree of freedom model. In this way it would be possible to compute the numerical values of the parameters, allowing to optimize the current skyhook control.

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