Multibody model for enhancing the dynamic behavior of an agricultural tractor

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ABSTRACT

A numerical model of the front axle suspension of a medium-range agricultural tractor is presented. The final goal is developing a numerical tool with real-time capabilities for possibly improving the dynamic response of the vehicle. The model consists of a multibody model for simulating the dynamics of the complete tractor and a hydraulic model of the suspension actuation system, integrated in Simulink environment. The models run in co-simulation, driven by the input signals commanding the valves of the hydraulic cylinder, in a closed-loop system. Model validation has been carried out by using experimental data obtained from a test referred to as leveling maneuver, where the suspension displacement has been measured in addition to the cylinder controlling signals (normally available on board). The validated model proved quite accurate and reliable in predicting the dynamic behavior of the tractor during the tested maneuver. Further investigations are ongoing to achieve real-time compliance, as well as to verify the model performance in different operating conditions.

Keywords: Vehicle dynamics, Co-simulation, Active suspension, Real-time compliance.

1 INTRODUCTION

Numerical simulations have become an essential tool to support the design process of complex mechanical systems, also thanks to higher computational resources typically available to manufacturers. In a software environment, it is possible to model real operating conditions for predicting reliably the system behavior, hence reducing the amount of field tests required. This leads to higher data availability since the early design stage and thus to higher optimization opportunities. In the automotive industry, multibody-based models are among the most used tools to investigate vehicle dynamics and assess the performance in different working conditions. Numerous works dealing with agricultural vehicles can be also found [1-4].

This study aims at developing a multibody model of the front axle suspension of an agricultural tractor, that must be coupled with a model of its driving hydraulic system. The activity has been carried out in collaboration with the company CNH Industrial (Amsterdam, NL), and focused on a medium-range tractor. Its front axle suspension is characterized by a proprietary architecture (referred to as Terraglide™) and hydraulic actuation. The final goal is implementing a model that can run in real-time, to possibly enable an optimization of the system dynamic response [5-7].

The developed numerical tool consists of a multibody model of the complete tractor and a hydraulic model of the front axle suspension, integrated in Simulink (Mathworks, Natick, MA, USA) environment. The multibody model has been created with the software Simcenter 3D

(Siemens, Plano, TX, US). The hydraulic model of the suspension has been built with Amesim (Siemens, Plano, TX, US). Simulink environment is used as interface and control system for co-simulation [8-10].

The developed model will permit to predict the vehicle response in many different operating conditions through simulations, hence providing useful results to improve the performance of the real tractor. It will also allow improving the operator's comfort, as well as implementing predictive maintenance strategies, by predicting in advance the stresses and solicitations which could represent an issue in terms of durability of the machine [11-13]. After further developments, this tool could also give the possibility of implementing virtual sensing strategies, finally being able to improve the control logics of the machine's control unit in real time.

2 VEHICLE DESCRIPTION

The tractor object of the study is a New Holland T7 LWB (long wheelbase) with continuous variable transmission (CVT) and all-wheel drive (AWD) transmission system, which is a medium-range tractor (Fig. 1). The vehicle weight is in the order of 9 tons. These kinds of vehicles typically have no suspension systems on the rear wheels, the only deformable element between the road and the tractor's body being the tires. The absence of the rear suspension system is also related to the need of towing heavy loads while operating.

Figure 1. *New Holland T7 LWB CVT tractor.*

The operator's comfort is assured by the cabin suspension system and the seat suspension. The cabin is connected to the driveline by two rigid revolute joints in the front part, leaving the rotation around a transverse axis as the only degree of freedom, and two spring-damper suspensions on the rear. This represents a quite simple architecture, often adopted in the medium to high range tractors. The cabin is also connected to the transmission housing by a stabilizing bar (Fig. 2).

The front axle suspension system is of the suspended kind (Fig. 3). The front axle is rigidly connected to the suspension arm, which is, in turn, connected to the tractor frame by means of a spherical coupling (Fig. 2). Moreover, the front axle is connected by a cylindrical joint to the suspension rod, which is, in turn, connected to the engine support (i.e. the tractor frame) by another spherical joint. The suspension rod is acted upon by a hydraulically actuated suspension cylinder. Driving torque is provided to the front wheels by a driving shaft passing inside the suspension arm.

The steering system is hydraulically actuated by two cylinders, each one acting between the front axle and one wheel knuckle (Fig. 3). In the rear part of the tractor a Power Take Off (PTO) is present, to possibly transmit power to the implement or driving torque to the trailer, if any is present.

Due to NDA the actual values of all the parameters of the tractor and its components are not going to be reported.

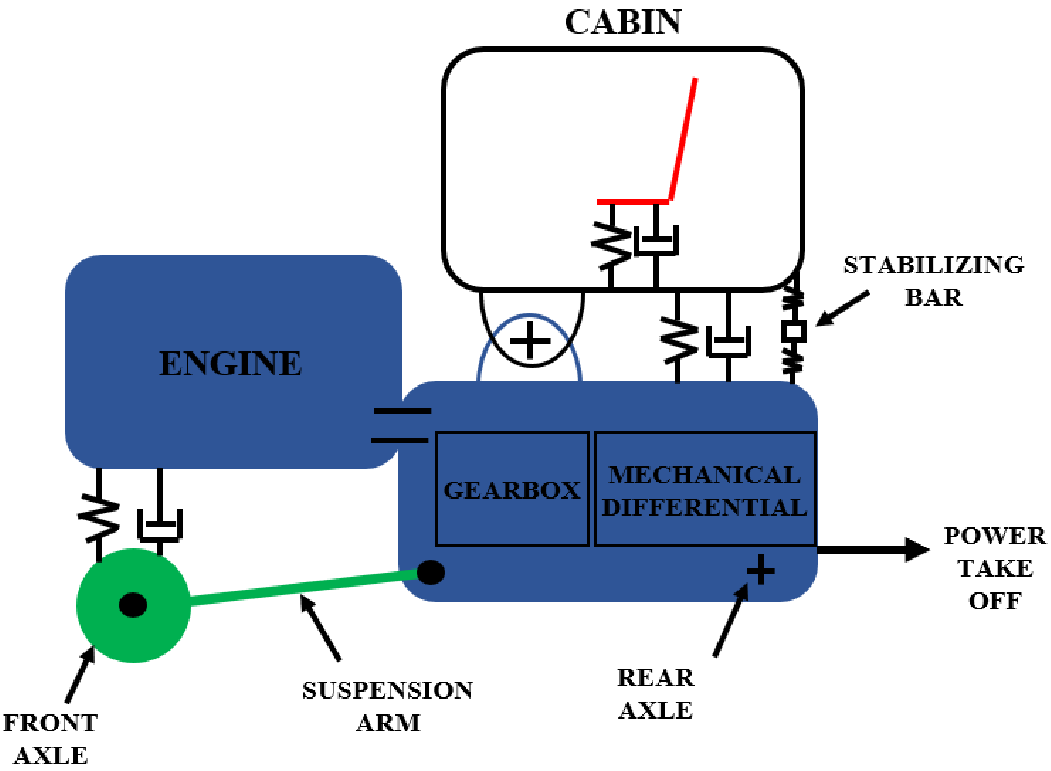

Figure 2. *Tractor architecture scheme (side-view).*

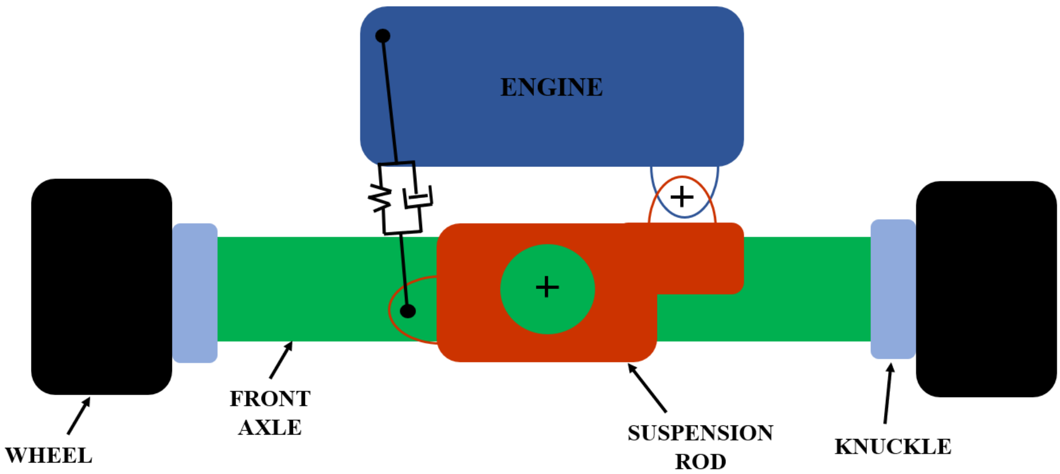

Figure 3. *Front axle suspension system scheme (rear view).*

3 NUMERICAL MODEL

3.1 Multibody model

A CAD model of the tractor has been created by means of the software CREO (PTC Inc., Boston, MA, US), including all the components which are fundamental for the correct characterization of the system. The Centers of Gravity (CoG) of the components, as well as their mass and inertia properties, have been determined by exploiting such model.

The multibody model has then been created in Simcenter 3D importing the model from the CAD software. It is composed by 11 rigid bodies (connected by ideal constraints) that completely characterize the system operation:

- Cabin
- Frame
- Front left and right knuckles

- Front left and right wheels
- Front axle
- Suspension rod
- Rear left and right wheels
- Cabin stabilizing bar

The frame takes into account the mass and inertia properties of the gearbox, the transmission housing and the engine.

The complete multibody model has 18 Degrees of Freedom (DoF). The front axle suspension subsystem, consisting in the front axle/suspension arm assembly and the suspension rod and the steering system has 3 DoF associated with it.

The cabin has been modelled as a rigid body, connected to the frame by a revolute joint and a suspension cylinder modelled as a spring-damper element described by lumped constant stiffness and damping parameters. The cabin's stabilizing bar has been modelled as a lumped mass-spring-damper system, hence adding one DoF to the model.

Tire-ground interactions have been currently defined by means of a simplified tire model that the adopted commercial software can handle. In this case a CDTire model has been taken into consideration, exploiting the Pacejka model to define the contact between tire and ground [14]. It's worth noting that, regarding suspension systems, tractors are frequently tested on tarmac with different road profiles. Hence, to obtain a numerical tool with computational time as low as possible, the use of contact models with deformable terrain is currently not considered of primary interest.

3.2 Co-simulation

The complete multibody model needs to be integrated with the hydraulic system model. The front axle suspension system is composed of a single, hydraulically actuated, cylinder between the suspension rod and its support, valves, accumulators and a hydraulic pump, driven by the engine.

The hydraulic circuit has been modelled, as previously said, with the software Amesim. In order to implement the required integration, a co-simulation approach has been adopted. The chosen environment for this operation has been the software Simulink. To this purpose, an interface has been created between Simcenter 3D and Simulink, so the two software are able to communicate with each other. The hydraulic system model in Amesim has been exported to Simulink. This enabled the suspension system model and the multibody model to communicate, using Simulink as control system for the co-simulation. The simulations can be run from the complete Simulink model (Fig. 4).

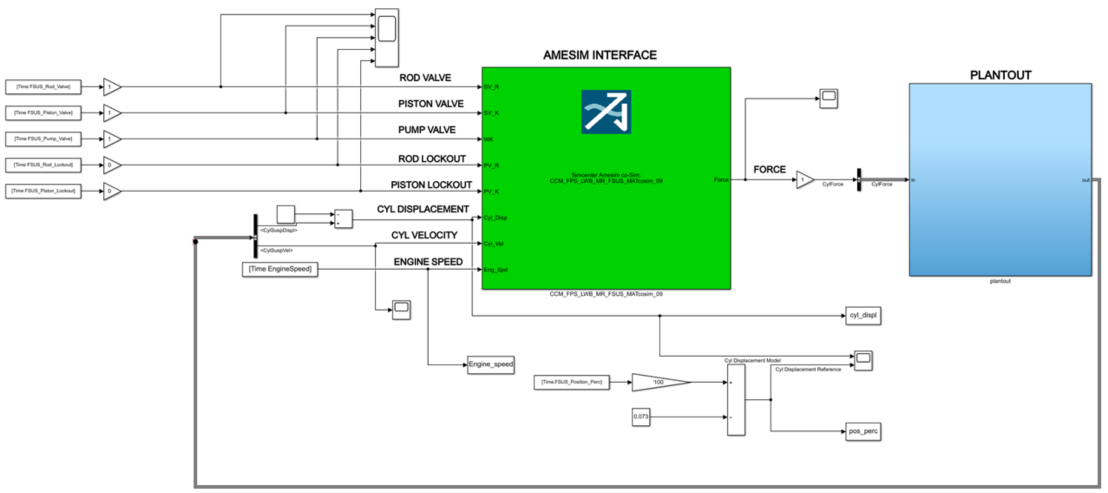

Figure 4. *Simulink model for co-simulation.*

The model is driven by the input signals commanding the valves of the hydraulic system, coming from experimental measurements on the field. The hydraulic system provides an output force, which is imposed as input to the hydraulic cylinder of the front axle suspension in the multibody dynamic model. Then, the latter gives as outputs the velocity and displacement of the suspension cylinder, which are fed back as inputs, creating a closed loop system, as it can observed in Fig. 5.

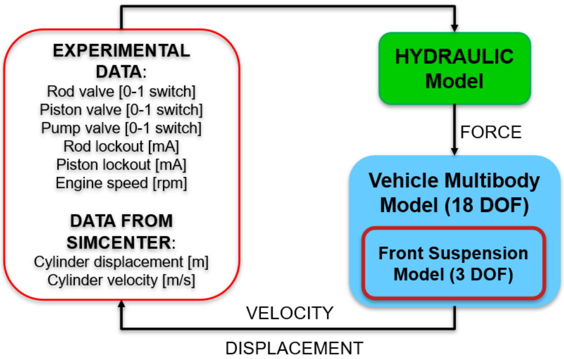

Figure 5. *Co-simulation conceptual schematic.*

More in detail, the valves that are used to drive the system are the following ones (Fig. 6):

- Rod valve
- Piston valve
- Pump valve
- Rod lockout: valve commanding the flow to and from the accumulator of the rod side
- Piston lockout valve commanding the flow to and from the accumulator of the piston side

The other signals needed by the hydraulics are the velocity and displacement of the suspension cylinder, and the engine speed (Fig. 6). The latter is necessary because the hydraulic pump is driven by the engine. Such data have been collected during experimental tests as well, and are given as input to the hydraulic system. Velocity and displacement are used to calculate the exact force that is provided as an input to the multibody model, i.e. the force generated by the suspension cylinder during the simulation.

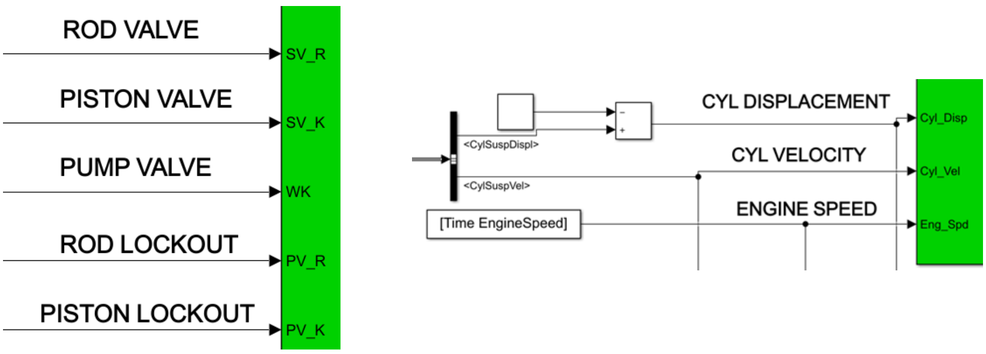

Figure 6. *Hydraulic inputs detail.*

The implemented model has been preliminarily validated by performing an experimental test referred to as leveling maneuver. The tractor begins the simulation with the suspension cylinder in its nominal position at an equilibrium condition. Then, the suspension cylinder is brought to its inferior end of the stroke (fully compressed cylinder). This position is maintained for about 15 s. The cylinder is then brought to its superior end of the stroke (fully extended), again keeping the position for a certain time, finally returning to the initial position until the simulation is terminated. The total simulation time is of 60 s.

In such test, in addition to the cylinder controlling signals normally available, the distance between the two attachment points of the suspension was also measured, through a position transducer.

By exploiting this model, other operating conditions can be simulated. To impose a certain motion to the machine, a speed driver or a certain value of torque can be input to the revolute joints connecting the wheels to tractor. This enables the possibility of performing simulations while the tractor is moving at a given speed on a selected terrain (e.g. a track with bumps).

4 PRELIMINARY RESULTS

The first results provided by the validated model show that a quite satisfactory accuracy could be achieved. The comparison between the suspension cylinder displacements of the real vehicle and the simulated ones is reported in Fig. 7 (the actual displacement values are omitted due to NDA). As it can be observed, the model is able to replicate in quite a precise way the behavior of the tractor suspension during the test. The superior and inferior ends of the stroke of the suspension are closely matched.

During the transients, especially in the first part of the simulation, there are some discrepancies between the simulated model and the reference. This is due to the dynamic response of the hydraulic system, partially affected by the presence of the accumulators which could not be perfectly modelled due to the lack of some relevant data. Nonetheless, the observed behavior is considered still acceptable.

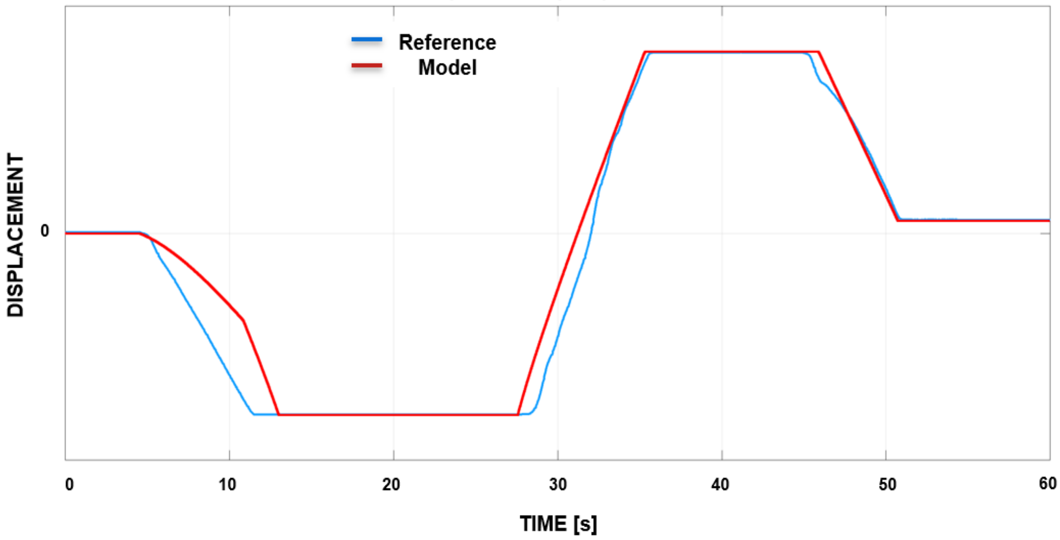

Figure 7. *Leveling maneuver results.*

The computational time has been analyzed in order to assess the suitability of the model for real-time applications. Real-Time Compliance (RTC) has been evaluated by comparing the computational time required for running the simulation (t_c) and the real (i.e. physical) duration of the simulated event (t_r):

$$\frac{t_c}{t_r} = \begin{cases} \geq 1: not\ real - time\ compliant \\ < 1: real - time\ compliant \end{cases} \tag{1}$$

During the leveling maneuver previously described, the model required a computational time almost double compared to the real duration of the simulated event (60 s), hence the RTC requirement being not met:

$$\frac{t_c}{t_r} = \frac{110}{60} = 1.83 \tag{2}$$

If a more challenging force input is directly imposed to the suspension cylinder, such as a sinusoidal wave simulating the tractor travelling along a rough surface, the performance in terms of RTC may even worsen. Therefore, while the preliminary results are promising in terms of accuracy and reliability, further investigations are required to achieve RTC for all possible operating conditions of the tractor.

5 CONCLUSIONS

A numerical model of the front axle suspension of an agricultural tractor has been developed. The model, based on the co-simulation of a multibody model of the complete vehicle and a hydraulic model of the suspension actuation, proved quite effective.

Additional measurements on the field are ongoing, in order to verify and further refine the model for different, more challenging, operating conditions. In particular, an experimental campaign tailored to the validation of the cabin response (to better evaluate the operator's comfort) is being designed.

Different strategies for further improving the performance of the model in terms of accuracy are being evaluated and tested. The definition, development and validation of possible methods to assess and improve the computational performance of the implemented numerical tools are under investigation as well, to possibly achieve Real-Time Compliance.

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