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Numerical analysis of the effect of tire characteristics, soil response and suspensions tuning on the comfort of an agricultural vehicle

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Abstract

The paper focuses on the numerical investigation of riding comfort of an agricultural vehicle. The analysis is carried out combining a multi-body model of a tractor with a tire–soil interaction model. The multi-body model schematizes the tractor through several rigid bodies representing the chassis, the cabin, the seat and the tires. Model parameters (masses, suspension parameters) were identified by means of full scale tests on a four-post test-rig. Tire–soil interaction model allows computation of the forces exchanged at the contact interface considering soil deformability and the 3D tread design. Several simulations were performed considering the vehicle running at constant speed over a deformable soil; different combinations of suspensions parameters were analyzed to determine their effect on driver comfort evaluated in terms of vertical acceleration on the seat. In addition, the analysis was completed with four different scenarios coupling two different tires with two different soils.

Keywords: Multibody model; Tire; Tread pattern; Agricultural soil; Suspension; Driver comfort

1. Introduction

Agricultural tractors have to accomplish a multiplicity of different missions: they should develop high thrusts on deformable soils, they could be used for road and off-road transportation, they should guarantee adequate speed and handling performance on ordinary roads and they should provide good comfort levels. This last aspect is related to the vibration induced on the vehicle chassis by irregularity and deformation of the track and by the use of lugged tires [1]. Due to the continuous increase of tractors speed, issues relevant to comfort levels are becoming critical especially for their impact on riding safety. In fact, besides undermining operator's health on a long-time base [1–3], the exposure to high vibration levels affects the efficiency and the alertness of the operator [4–6], thus leading to unsafe operating conditions. Considering that the rear axle of tractors is often unsuspended and suspensions on the front axle are usually locked during field operation, other suspension levels are introduced to guarantee adequate riding comfort. The first suspension level is represented by radial flexibility of tires. The second level is located between the chassis and the tractor cabin while the driver seat, which is often suspended, constitutes the last level.

This work analyzes the comfort levels of a tractor during field operation from a numerical point of view. The aim of the analysis is to determine the optimal combination of suspension parameters which leads to minimize the acceleration levels transmitted to the operator. The model used in the numerical analysis combines a multi-body model of tractor and a tire–soil interaction model. The tractor model consists of a lumped parameters model whose data were identified through a series of tests carried out with a four-post test bench [7,8]. The tire–soil interaction model

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allows the computation of the contact forces developed by a lugged tire operating on a deformable soil; the model takes into account the 3D geometry of the tread surface and the main mechanical characteristics of the soil. Thus, the proposed model includes the most important factors influencing riding comfort: terrain deformation, tread pattern design, tire flexibility and suspensions characteristics. Also soil irregularity was considered.

Simulations were carried out assuming a tractor moving at 7 km/h over a deformable soil; several combinations of suspensions parameters were tested in order to evaluate the improvement with respect to nominal settings. The analysis was repeated with four scenarios combining two tires with different size and tread pattern with two terrains with different mechanical responses.

The paper is organized as follows: the first section is focused on the multi-body model of the tractor; the second part of the article deals with the tire–soil interaction model. The last section presents the numerical analysis aiming at optimizing the suspensions parameters.

2. Multi-body model of the vehicle

The modeled agricultural tractor is a high-range tractor, whose mass and main dimensions are reported in Table 1.

The tractor is composed of a frame (vehicle body) on which are placed the engine and the cabin. The cabin is connected to the frame by means of three passive pneumatic suspensions (air springs). Independent actively controllable double wishbone suspensions join the front tires with the frame. A pair of electronically controlled hydro-pneumatic actuators allow to regulate the length of the suspensions. Two working conditions are supported by the suspension system: during field operations (tilling, ground compaction, etc.), the actuators can be locked up (the suspension is thus rigid) in order to increase traction, whereas, when the vehicle is running on ordinary roads, the actuators can be unlocked in order to damp vehicle pitch. The front suspension can be manually switched on or off by the operator. On the contrary, no suspensions are present between the rear axle and the frame. Finally a pneumatic spring and a damper connect the seat with the cabin.

A sketch of the proposed tractor model is presented in Fig. 1; the model is made up of several rigid bodies linked by linear spring-damper elements:

- one rigid body representing the vehicle chassis having three d.o.f. (heave, pitch and roll); this body includes the rear axle, which is assumed to be rigidly linked to the chassis;

Table 1
Vehicle mass and geometry.

Total mass	[kg]	10,320
Wheelbase	[m]	3.06
Front track	[m]	2.11
Rear track	[m]	2.01

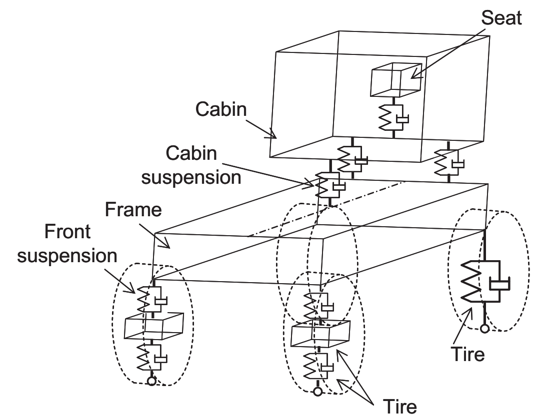

Fig. 1. MB vehicle model.

- one rigid body representing the cabin, characterized by three d.o.f. (heave, pitch and roll);
- two rigid bodies representing the front unsprung masses (the examined vehicle presents independent front suspensions), each one having one d.o.f. (heave);
- one rigid body having one d.o.f (heave), representing the seat and the load mounted on it which simulates the equivalent mass of the operator;
- four rigid rings representing the outer part of the four tires (the part contacting the ground); each ring presents a vertical motion and a rotation along the hub.

Spring-damper elements represent the front suspension of the chassis and the suspension system of cabin and of the seat; the rigid ring of each tire is connected to the corresponding hub through spring-damper elements which represent the front and rear tires vertical stiffness and damping.

2.1. Parameters identification and model validation

Several experimental tests were performed on the examined tractor with the purpose of identifying the parameters of the multi-body model and to obtain a validation of the model itself. During the tests, the vehicle was instrumented with

- four one-axis piezoelectric accelerometers placed in correspondence of each hub to measure their vertical accelerations;
- four one-axis piezoelectric accelerometers placed in correspondence of each attachment point of the suspensions on the chassis;
- an inertial gyroscopic platform in order to measure the accelerations of the cabin along the three axes of motion (longitudinal, x, lateral, y, and vertical, z) and the angular velocities of pitch (rotation about axis y: ω_y), roll (rotation about axis x: ω_x) and yaw (rotation about axis z: ω_z);
- two three-axis piezoelectric accelerometers placed in correspondence of the seat plane and of the back support in order to evaluate the operator comfort;