CAR VERTICAL DYNAMICS SIMULATIONS USING BOTH AN IN-HOUSE 7 DOF MODEL SIMULATOR AND CARSIM COMMERCIAL SOFTWARE

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The car vertical dynamics simulations in this paper concern only the roll and the pitch motion of the car body. Two different simulators are aimed to be used in parallel. The first simulator considered is CARSIM commercial software, while the second variant is an in-house simulator based on a 7 DOF car vertical dynamics model, which concerns only the vertical dynamics of the car, neglecting the small motions in the horizontal plane (longitudinal and transversal oscillations). This in-house car vertical dynamics simulator is written in Simulink. The results presented in this paper are only CARSIM simulations, further work will compare these CARSIM simulations with the results obtained on the same case study using the in-house 7 DOF model simulator.

Keywords: 7DOF car model, vertical dynamics, 3D simulator, Matlab/Simulink, CARSIM software, vertical displacements, pitch and roll angles.

1. Introduction

Vehicle dynamics has been intensively studied for more than a hundred years, the automobile representing a subject of major interest for the society [1,2]. Vehicle dynamics is a complex research topic, involving various studies concerning: simulation of random road profiles and tyre behavior [2,3], passive or (semi)active suspensions [4,5], car lateral motion [6,7], vehicle vibrations [1], etc. In the recent decades, based on the development of performing computers, simulations have gained importance in vehicle dynamics [7-9], even if simulating car dynamics is at first view less attractive than simulating airplane dynamics since cars are much more available for real ride. Thus, various dynamic car simulators have been built and commercialized, especially simulators for racing or representing an improvement/complement to traditional video games. Of course, real measurements of car dynamics and vibrations are affordable and can always be performed if necessary, without difficulty, but car dynamics simulators can be used to save research time and resources.

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With the aim of developing such a dynamic car simulator, the main difficulties consist in simulating the wheel/road dynamic contact and in dynamically reproducing the vertical displacements and accelerations of the driver seat, using a Danaher Thomson linear actuator with ball screw drive [10] and a real-time control system. In our case, CARSIM software [11] is used as full car dynamics simulator for generating the vertical vibrations induced under the driver seat by the car ride on the considered road profile. On the other hand, an in-house simulator based on a 7 DOF car vertical dynamics model, concerning only the vertical dynamics of the car and neglecting the small motions in the horizontal plane (longitudinal and transversal oscillations), is also aimed to be further used.

These car vertical dynamics simulations using CARSIM or the in-house 7 DOF model simulator will be used for further studies on wheel-road adherence, passenger/driver comfort and the use of appropriate suspension shock absorbers to improve both wheel-road adherence and passenger/driver comfort. This adherence and comfort combined criterion represents a primary but very important element in an overall intelligent transportation strategy. Thus, a driver experiencing increased comfort will drive more cautiously, while an increased adherence of the vehicle means safer traffic conditions.

2. CARSIM model for car vertical dynamics

Several commercial car dynamics software packages are available. CARSIM software is one of these well-known 3D car dynamics simulators, being provided by Mechanical Simulation Corporation [11] (http://www.carsim.com/). Numerous simulations have already validated CARSIM software over the years, the results being almost as accurate as real experiments, thus the simulations performed using CARSIM can be considered as virtual experiments.

Generally, CARSIM 8.1.1 simulates a complete 3D vehicle-suspension multibody model, concerning the car vertical dynamics, as well as the lateral and longitudinal motions. The full CARSIM model is *“represented mathematically by 113 ordinary differential equations that describe the kinematical and dynamical behavior. This full model is composed of 32 bodies, has 16 multibody DOF, 41 multibody coordinates, 49 auxiliary coordinates, 16 multibody speeds, 7 auxiliary speeds, and has 127 active forces and 93 active moments”* [11].

In our case, CARSIM software is used to simulate simplified motions, such as the previously studied half-car vertical 2D dynamics corresponding to the “bicycle” model [12]. In this paper, only the vertical dynamics of the car is studied, involving the roll and the pitch motion of the car body and neglecting the small motions in the horizontal plane (longitudinal and transversal oscillations). Such a simplified motion can be studied using the complex CARSIM software, which is much more general (has numerous DOF as described above, much more than the 7 DOF considered by our simplified vertical dynamics model, described in next section), by considering an appropriate/simplified case study, e.g.: considering a straight road, without lateral or longitudinal slips, neglecting those degrees of freedom (DOF) with minor influence on the vertical dynamics, etc.

3. 3D car vertical dynamics 7 DOF model for in-house simulator

Besides CARSIM commercial software, a second variant for our car dynamics simulations is an in-house simulator based on a 7 DOF car vertical dynamics model, which concerns only the vertical dynamics of the car, neglecting the small motions in the horizontal plane (longitudinal and transversal oscillations). Fig. 1 shows the 3D dynamic 7 DOF model [13-15] used to study the vertical interaction between car and road, considering both the roll and the pitch motion of the car. The case of independent suspensions both for the front and rear part of the car is considered here.

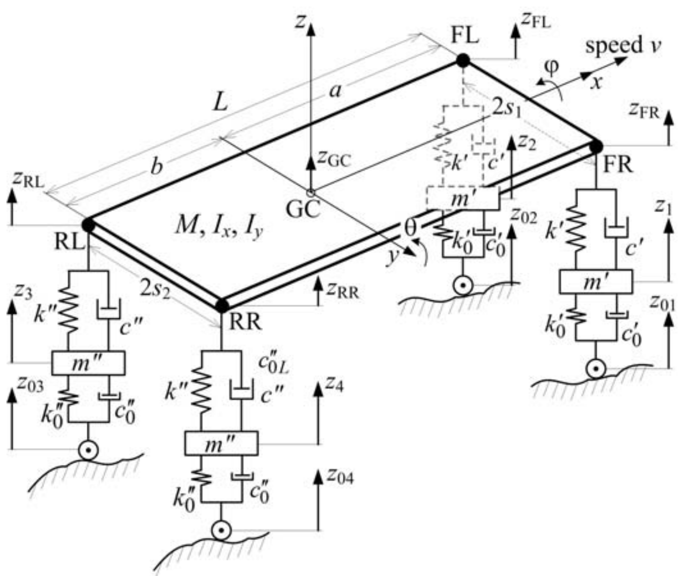

Fig. 1 – 3D car vertical dynamics 7 DOF model [15]

The 7 DOF of the considered 3D vertical model are: the vertical displacement z_{GC} of the gravity center GC of the car body (sprung mass), the roll angle φ of the car body (around the x axis passing through the gravity center GC), the pitch angle θ of the car body (around the y axis passing through GC), the vertical displacement z_1 of the front right wheel center (front right wheel hop), the vertical displacement z_2 of the front left wheel center (front left wheel hop), the vertical displacement z_3 of the rear left wheel center (rear left wheel hop) and the vertical displacement z_4 of the rear right wheel center (rear right wheel hop).

The vertical displacements z_i (i=1,2,3,4) are obviously calculated with respect to the equilibrium position.

At time t, the vertical profile of the road (road roughness) corresponding to the front right wheel is denoted by $z_{01}(t)$, the road roughness corresponding to the front left wheel is denoted by $z_{02}(t)$, the road roughness corresponding to the rear left wheel is denoted by $z_{03}(t)$, finally the road roughness corresponding to the rear right wheel is denoted by $z_{04}(t)$. In fact, since a straight road is considered here, the road roughnesses $z_{01}(t)$ and $z_{02}(t)$ are encountered by the front wheels (right and, respectively, left wheels) at time t, while the right and left rear wheels encounter the same road roughnesses after $\Delta t \cong \frac{L\cos\theta}{v}$ (so at $t+\Delta t$), where L is the wheelbase, θ the pitch angle and v the constant car speed. Thus: $z_{01}(t)=z_{04}(t+\Delta t)$ and $z_{02}(t)=z_{03}(t+\Delta t)$.

The 7 DOF model contains two levels of elastic and damping elements: one level between the wheels and the road, characterized by the stiffness coefficients k_0' and k_0'' of the tyres and the damping coefficients c_0' and c_0'' of the tyres; the second level between the wheels and the body (vehicle suspension), characterized by the spring rates of suspension k' and k'' and the damping coefficients c' and c'' of the shock absorbers. Here $'$ corresponds to front wheels, while $''$ corresponds to rear wheels.

The 7 DOF car/road vertical interaction model in Fig. 1 implies the following geometrical and inertial characteristics:
• the distance a between the mass center GC of the sprung mass M and the front axle (passing through points FR and FL); • the distance b between the mass center GC of the sprung mass M and rear axle (passing through points RR and RL); • the car wheelbase L (obviously $L=a+b$);
• the front wheel track $2s_1$ (distance measured across the front axle from the center line of the front left tyre tread to the center line of the opposite front right tyre tread); • the rear wheel track $2s_2$ (distance between left and right rear wheels);
• the front left wheel unsprung mass m'; • the front right wheel unsprung mass m';
• the rear left wheel unsprung mass m''; • the rear right wheel unsprung mass m'';
• the mass M of the car body (sprung mass M), which normally takes values between M_{empty} (unloaded car case) and M_{full} (maximum admissible car loading case); • the moment of inertia I_{xx} (roll inertia) of the sprung mass M with respect to the longitudinal x axis passing through the mass center GC of the sprung mass;
• the moment of inertia I_{yy} (pitch inertia) of the sprung mass M with respect to the transversal y axis passing through the mass center GC of the sprung mass.

The vertical dynamics equations of the 7 DOF model are obtained using the Newton-Euler formulation, as provided in the literature [13-16]. The aerodynamic forces are neglected here. There are 3 scalar dynamic equations of the sprung mass: one in terms of vertical forces (z direction), one in terms of moments with respect to the longitudinal x axis and the third one in terms of moments with respect to the transversal y axis. Since the roll angle φ and the pitch angle θ are small, in this case the vertical dynamic equations of the car body can be written as follows [14-16]:

$$\begin{cases} M\ddot{z} = -(F_{\mathrm{FL}} + F_{\mathrm{FR}} + F_{\mathrm{RL}} + F_{\mathrm{RR}})\cos\varphi\cos\theta \\ I_x\ddot{\varphi} = (F_{\mathrm{FL}} - F_{\mathrm{FR}})s_1\cos\varphi\cos\theta + (F_{\mathrm{RL}} - F_{\mathrm{RR}})s_2\cos\varphi\cos\theta \\ I_y\ddot{\theta} = (F_{\mathrm{FL}} + F_{\mathrm{FR}})a\cos\theta - (F_{\mathrm{RL}} + F_{\mathrm{RR}})b\cos\theta \end{cases} \quad (1)$$

where the resulting forces at the points where the sprung mass is attached to the suspension system, i.e., FL, FR, RL and RR, are given by:

$$F_{\mathrm{FR}} = F_{c,\mathrm{FR}} + k'(x_{\mathrm{FR}} - x_1) - F_{e,\mathrm{bumper,FR}}, \quad F_{\mathrm{FL}} = F_{c,\mathrm{FL}} + k'(x_{\mathrm{FL}} - x_2) - F_{e,\mathrm{bumper,FL}},$$
$$F_{\mathrm{RL}} = F_{c,\mathrm{RL}} + k''(x_{\mathrm{RL}} - x_3) - F_{e,\mathrm{bumper,RL}}, \quad F_{\mathrm{RR}} = F_{c,\mathrm{RR}} + k''(x_{\mathrm{RR}} - x_4) - F_{e,\mathrm{bumper,RR}}. \quad (2)$$

Here $F_{c,\mathrm{FR}}$ stands for the damping force given by the front right shock absorber. As for $F_{e,\mathrm{bumber,FR}}$, it designates the elastic striking force when the piston hits either the rebound bumper ($F_{e,\mathrm{bumber,FR}} < 0$ case) or the compression bumper ($F_{e,\mathrm{bumber,FR}} > 0$ case) of the front right suspension. Obviously, similar notations are used for the front left (FL), rear right (RR) and rear left (RL) suspensions.

The dynamic equations of the front and rear wheels are as follows [14,15]:

$$\begin{cases} m'\ddot{x}_1 = F_{\mathrm{FR}} - c_0'(\dot{x}_1 - \dot{x}_{01}) - k_0'(x_1 - x_{01}) \\ m'\ddot{x}_2 = F_{\mathrm{FL}} - c_0'(\dot{x}_2 - \dot{x}_{02}) - k_0'(x_2 - x_{02}) \\ m''\ddot{x}_3 = F_{\mathrm{RL}} - c_0'(\dot{x}_3 - \dot{x}_{03}) - k_0'(x_3 - x_{03}) \\ m''\ddot{x}_4 = F_{\mathrm{RR}} - c_0'(\dot{x}_4 - \dot{x}_{04}) - k_0'(x_4 - x_{04}) \end{cases} \quad (3)$$

The second order differential equations of motion (1) and (3) can be easily transformed in a system of 14 first order explicit ordinary differential equations, ready to be numerically integrated by the Runge-Kutta method.

An in-house car vertical dynamics simulator based on the numerical integration of equations (1) and (3) has been realized in Simulink, the dynamic equations being implemented as C MEX S-functions from specifications and source code written in Ansi-C compatible.

4. Case study and CARSIM results

This paper presents only results obtained using CARSIM software, since the in-house simulator based on a 7 DOF car vertical dynamics model is still in its testing phase. A so-called CARSIM "C-Class Hatchback" car model is considered in this case study, with the following geometrical and inertial characteristics:

- car wheelbase $L = 2.578\ [\mathrm{m}] = a + b$, with $a = 1.016\ [\mathrm{m}]$ and $b = 1.562\ [\mathrm{m}]$;
- mass *M* of the car body (sprung mass) $M = 1.276\ [\mathrm{t}]$;
- pitch inertia $I_\theta = I_{yy} = 1.523\ [\mathrm{t}\cdot\mathrm{m}^2]$ and roll inertia $I_\varphi = I_{xx} = 0.606\ [\mathrm{t}\cdot\mathrm{m}^2]$;
- front unsprung mass (mass of one front wheel plus half of the front axle mass): $m' = \frac{71}{2}$=30.5 [kg]; • rear unsprung mass $m'' = 30.5\ [\mathrm{kg}]$ (similarly).

The simulations are performed for a constant car speed of $v = 60\ [\mathrm{km/h}]$. The following elastic characteristics are considered for the suspensions and tyres:

- $k' = k'' = 27\ [\mathrm{kN/m}]$; • $k_0' = k_0'' = 228\ [\mathrm{kN/m}]$ (correspond to 205/55 R16 tyres).

The damping law corresponding to the shock absorbers considered both in front and rear suspensions of our CARSIM simulations is represented in Fig. 2.

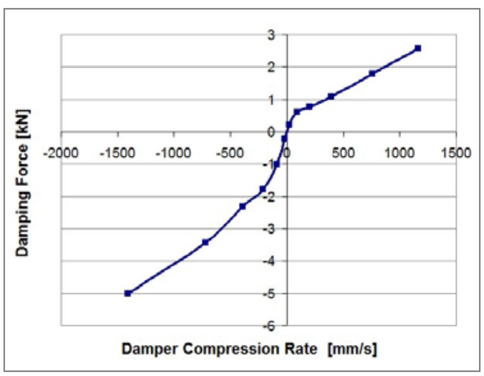

Fig. 2 – Damping law corresponding to the considered shock absorbers [11]

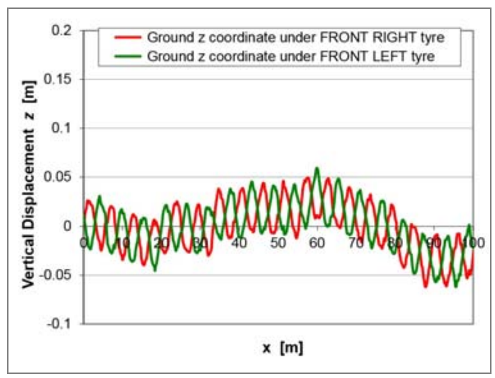

Fig. 3 – Road profile corresponding to the left, respectively right tyres

Fig. 3 shows the road profile considered under the left and, respectively, right tyres. As it can be observed, the road profile under the left tyre is quite in antiphase with the road profile under the corresponding front/rear right tyre. The road profile was considered here as a sum between a real random road profile already used in our previous studies [10,15] and a simple sinusoidal road profile $z_0(t) = 0.025\cdot\sin(2\pi\cdot 3\cdot t)$ [m], with an amplitude of 2.5cm and a frequency of 3Hz.

Fig. 4 shows the vertical displacements of the mass center of the sprung mass and of the front (right and left) wheels, as well as the considered road profile, between 0 and 7 sec. The 3D vertical motion of the car is described also by the pitch and roll angles (Fig. 5). Fig. 6 shows the accelerations of the sprung mass and of the front (right and left) wheels, between 0 and 4 sec, while Fig. 7 shows the front right (FR) wheel vertical forces: the FR tire vertical force, the FR suspension damping force and spring force. According to the first equation (2), their difference must be approximately equal to $m'\ddot{x}_1$, which is the case. This CARSIM simulation provides numerous other car dynamics variables, e.g., tyre compression, suspension jounce, damper compression rate, damping force, etc.

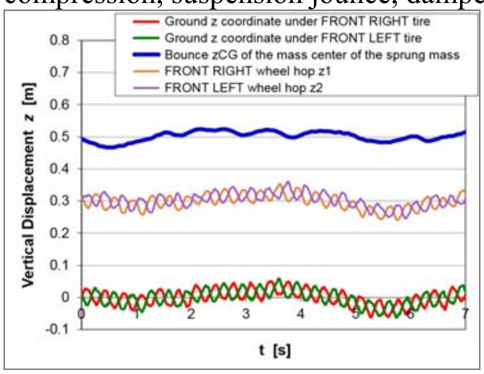

Fig. 4 – Vertical displacements [mm]

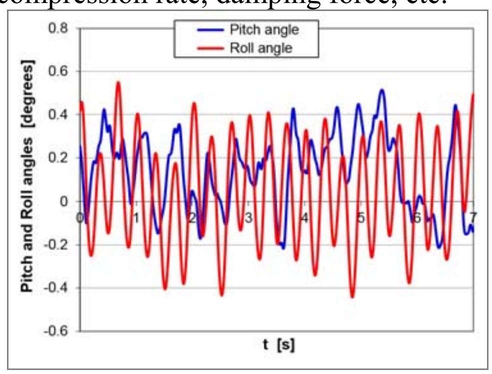

Fig. 5 – Pitch and roll angles [º]

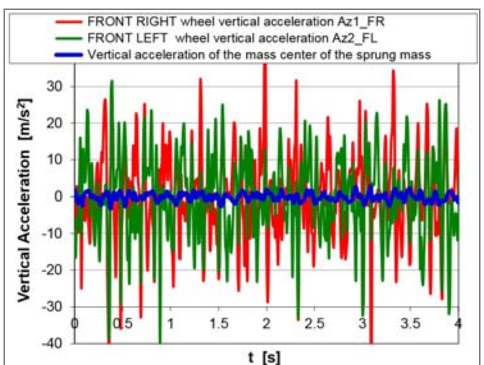

Fig. 6 – Vertical accelerations [mm/s^2]

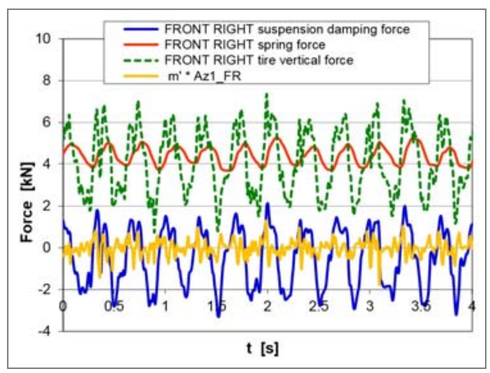

Fig. 7 – Front right wheel vertical forces [kN]

5. Conclusions

The results presented in this paper concern a simulation using CARSIM of a hatchback car 3D vertical dynamics. In parallel, an in-house 7 DOF model simulator has been developed, being still in its testing phase. Further tests will try to validate our in-house Matlab/Simulink simulator (its results must be in good agreement with those provided by CARSIM software for the same case study), which is aimed to be further used for studies on wheel-road adherence, passenger comfort and the use of appropriate suspension shock absorbers to improve both adherence and comfort. This in-house simulator will also be used to validate a road response simulator, designed as a reconfigurable haptic interface that includes real-time wheel/road dynamic contact simulation in its control system.

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