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VEHICLE MODEL FOR DYNAMICS ANALYSIS AND HIL SIMULATION

MODEL VOZIDLA PRO DYNAMICKOU ANALÝZU A HIL SIMULACÍ

Abstract

The paper describes design mathematical model of vehicle directional dynamics. The simulation model has been designed in MATLAB/Simulink environment. The vehicle model consists of three main subsystems (vehicle body model, wheel model, tire model). Vehicle tests for evaluating performance of vehicle control devices are often time consuming, expensive, and not reproducible. The hardware-in-the-loop (HIL) simulation is promising on this matter since it provides time- and cost-effective ways of vehicle testing with repeatability.

Abstrakt

Příspěvek popisuje tvorbu matematického modelu směrové dynamiky vozidla. Simulační model byl vytvořen v programu MATLAB/Simulink a skládá se ze tří hlavních částí (modely vozidla, kola a pneumatiky). Reálné jízdní zkoušky pro ověření funkčnosti řídících systému vozidla jsou často časově náročné, drahé a nereprodukovatelné. Simulace s využitím metody hardware-in-the-loop (HIL) umožňuje časově a cenově efektivní způsob testování s možnosti opakování jízdních situací.

1 INTRODUCTION

The degrees-of-freedom are numerous, with six-degrees-of-freedom in the chassis movement for a single-body vehicle (longitudinal, lateral, heave, yaw, pitch, and roll motion), and additional degrees-of-freedom in the wheels, engine, axles, etc. The vehicle is a true multi-variable process, with complex couplings between actuator inputs and the controlled entities. For example, braking during a cornering maneuver affects the yaw response of a vehicle. Most of the dynamics of the vehicle are also nonlinear.

2 VEHICLE AND TIRE DYNAMICS

In order to simulate a vehicle dynamics is necessary to develop a vehicle model. The vehicle model developed consists of three subsystems:

- vehicle body model
- wheel model
- tire model

2.1 Vehicle Body Model

I designed the three-dimensional dynamic model of a vehicle for simulation using MATLAB/Simulink. I prepared the main parts of the vehicle model using the programming language C. This is the basic approach to design various simulation models based on differential and algebraic

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equations describing the vehicle movement. This method has several advantages. If we create the mathematical model, containing many differential equations, our work is faster and finding mistakes is easier. Other advantage is the simple implementation for various versions of MATLAB issues.

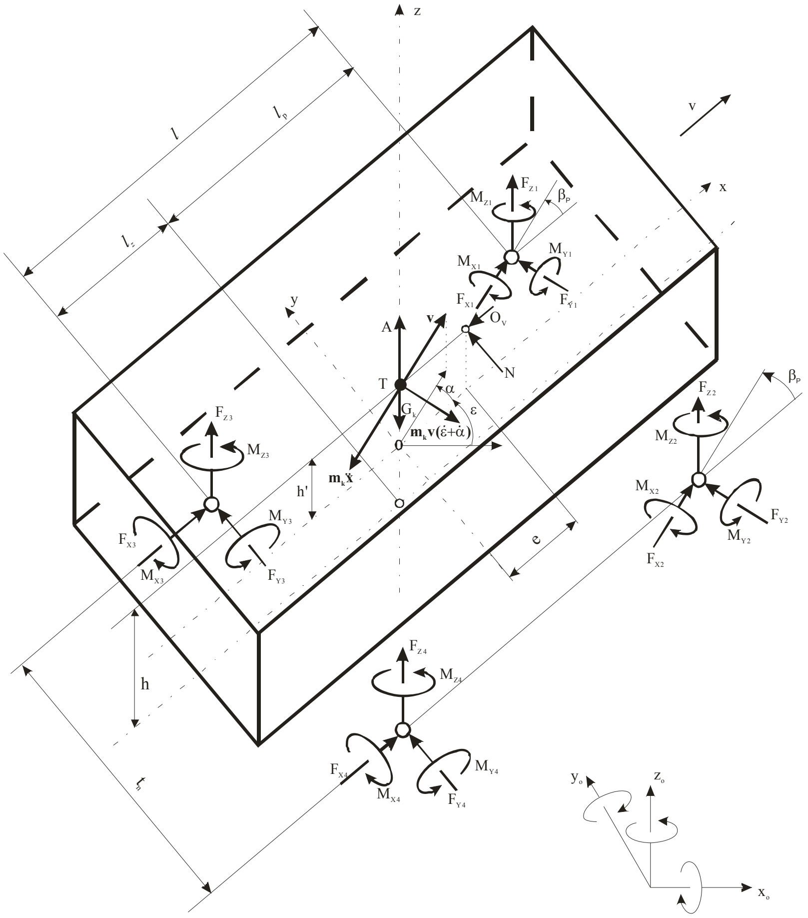

Fig. 1 Scheme of the vehicle model

$$m\ddot{x} = F_{X1} + F_{X2} + F_{X3} + F_{X4} - O_V \,, \tag{1}$$

where:

m – vehicle mass [kg],

$\ddot{x}$ – vehicle longitudinal acceleration [m·s^{-2}],

F_{Xi} – longitudinal tire force [N],

O_V – aerodynamic resistance [N].

$$m\dot{x}(\dot{\varepsilon} + \dot{\alpha}) = F_{Y1} + F_{Y2} + F_{Y3} + F_{Y4} + N \,, \tag{2}$$

where:

$\dot{x}$ – vehicle longitudinal velocity [m·s^{-1}],

$\dot{\varepsilon}$ – yaw rate [rad·s^{-1}],
$\dot{\alpha}$ – slip angle [rad·s^{-1}],
F_{Yi} – lateral tire force [N],
N – side-wind force [N].

$$J_Z\ddot{\varepsilon} = \left(F_{Y1}+F_{Y2}\right)l_P - \left(F_{Y3}+F_{Y4}\right)l_Z + \left(-F_{X1}+F_{X2}-F_{X3}+F_{X4}\right)\frac{t_n}{2} + Ne\,, \tag{3}$$

where:

e – distance external lateral force [m],
J_Z – vehicle yaw moment of inertia [kg·m^2],
l_P – distance front axle to vehicle centre of mass [m],
l_Z – distance rear axle to vehicle centre of mass [m],
t_n – wheel track [m],
$\ddot{\varepsilon}\,,\dot{\varepsilon}\,,\varepsilon$ – yaw angle [rad·s-^{2}, rad·s-^{1}, rad].

$$\begin{aligned} J_Y\ddot{\varphi} &= -K_\varphi\dot{\varphi} - C_\varphi\varphi + Gh_k\varphi - \left(F_{Z1}+F_{Z2}\right)l_P + \left(F_{Z3}+F_{Z4}\right)l_Z \\ &+ \left(F_{X1}+F_{X2}+F_{X3}+F_{X4}\right)h + \left(-F_{Z1}-F_{Z2}-F_{Z3}-F_{Z4}\right)f\left(h-r_d\right)' \end{aligned} \tag{4}$$

where:

C_φ – pitch stiffness [N·m·rad^{-1}],
f – coefficient of rolling resistance [-],
F_{Zi} – radial tire force [N],
h – height of vehicle centre of mass [m],
h_k – distance between centre of gravity and pitch axis [m],
J_Y – moment of inertia around y axis [kg·m^2],
K_φ – pitch damping [N·m·s·rad^{-1}],
r_d – wheel radius [m],
$\ddot{\varphi}\,,\dot{\varphi}\,,\varphi$ – pitch angle [rad·s^{-2}, rad·s^{-1}, rad].

$$J_X\ddot{\psi} = -K_\psi\dot{\psi} - C_\psi\psi + Gh_k\psi + \left(F_{Y1} + F_{Y2} + F_{Y3} + F_{Y4}\right)h$$
$$+\left(F_{Z1} - F_{Z2} + F_{Z3} - F_{Z4}\right)\frac{t_n}{2} \quad , \tag{5}$$

where:

C_ψ – roll stiffness [N·m·rad^{-1}],

J_X – moment of inertia around x axis [kg·m^2],

K_ψ – roll damping [N·m·s·rad^{-1}],

$\ddot{\psi}, \dot{\psi}, \psi$ – roll angle [rad·s-^{2}, rad·s-^{1}, rad].

2.2 Wheel Modelling

Figure 2 shows a schematic of a wheel rolling on the road. Wheel performs rotational motion (wheel angular velocity $\dot{\varphi}$) and longitudinal motion (wheel longitudinal velocity $\dot{x}$). We can create two differential equations [NOSKIEVIČ, P. 1999].

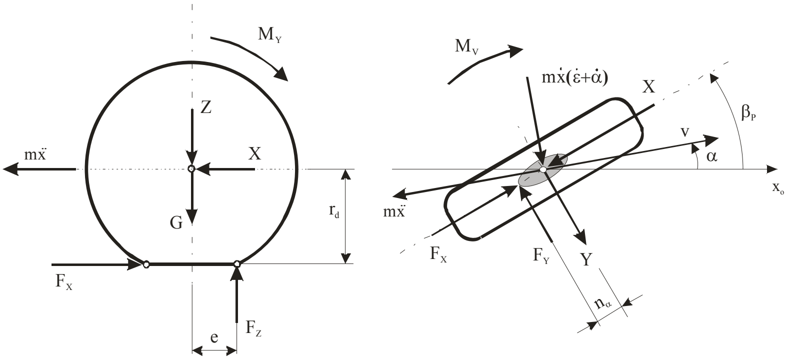

Fig. 2 Schematic of tire rolling

1) Differential equation defined longitudinal motion

$$m\ddot{x} = F_x - X \ , \tag{6}$$

where:

m - mass of the wheel [kg],

$\ddot{x}$ - wheel longitudinal acceleration [m·s^{-2}],

F_x - longitudinal tire force [N],

X - reaction force x axis [N].

2) Differential equation defined rotational motion

$$J_K\ddot{\varphi} = M_Y - F_x r_d \, , \tag{7}$$

where:

J_K - wheel moment of inertia around spin axis [kg·m^2],

$\ddot{\varphi}$ - wheel angular acceleration [rad·s^{-2}],

M_Y - torque applied to the wheel [Nm],

r_d - wheel radius [m].

2.3 Tire Model

There are many previous models which describe the tire forces generated at conditions of pure braking, driving, or cornering, as well as models which describe the tire forces resulting from mixed conditions of simultaneous braking (or driving) and cornering [KIENCKE & NIELSEN. 1999].

- HSRI (Highway Safety Research Institute)
- Magic Formula
- F-Tire
- TM-Easy
- SWIFT-Tyre (Short Wavelength Intermediate Frequency Tyre)

2.1 HSRI Tire Model

HSRI Tire Model is nonlinear mathematical model. The tire model needs radial force F_z, the slip angle of the tire α_k, the wheel longitudinal velocity $\dot{x}$ and the wheel angular velocity $\dot{\varphi}$ as input. From these variables it calculate longitudinal slip s_x. The tire model must be evaluated separately for every single tire. The longitudinal tire force F_x, the lateral tire force F_y and aligning moment M_V depending on the value of intermediate quantity s_R [VLK, F. 2000].

$$s_R = \frac{\sqrt{(C_S s_x)^2 + (C_\alpha tg\alpha)^2}}{\mu(1+s_x)F_z}, \tag{8}$$

where:

C_S - longitudinal stiffness [N·m^{-1}],

C_α - cornering stiffness [N·m^{-1}].

There are two situations between the tire and the road:

a) $s_R \leq 0{,}5$ - exist only pure adhesion between tire and road

b) $s_R > 0{,}5$ - mixed sticking/sliding fiction

Longitudinal tire force F_x and lateral tire force F_y are defined as

$$F_x = \begin{cases} C_S \dfrac{s_x}{(1+s_x)} & : s_R \leq 0{,}5 \\ C_S \dfrac{s_x}{(1+s_x)} \cdot \dfrac{s_R - 0{,}25}{s_R^2} & : s_R > 0{,}5 \end{cases}, \tag{9}$$

$$F_y = \begin{cases} C_\alpha \dfrac{\tan\alpha}{(1+s_x)} & : s_R \le 0{,}5 \\ C_\alpha \dfrac{\tan\alpha}{(1+s_x)} \cdot \dfrac{s_R - 0{,}25}{s_R^2} & : s_R > 0{,}5 \end{cases}, \tag{10}$$

Figure 3 show characteristics of HSRI Tire Model. We can see longitudinal force F_x and lateral force F_y in various loads F_z. Next graph show longitudinal force F_x for different values of friction coefficient. Final graph show aligning moment M_v for different values of loads F_z.

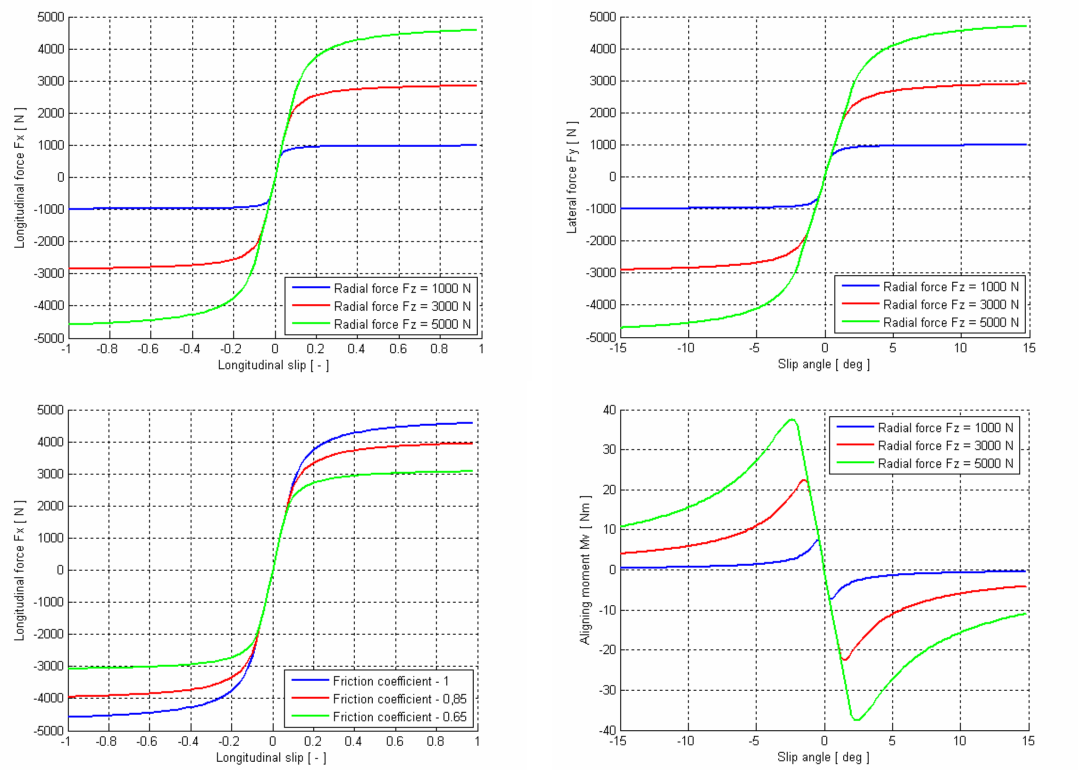

Fig. 3 Tyre force characteristics

2.3 Semi-Empirical Model

The most famous and general expression for this model is the following function, usually called “Magic Formula Tire Model”. Where $y(x)$ is F_x or F_y respectively if x is s_x or α.

$$y(x) = D\sin(C\arctan(Bx - E(Bx - \arctan(Bx)))), \tag{11}$$

where:

B - Stiffness factor [-],

C - Shape factor [-],

D - Peak factor [-],

E - Curvature factor [-].

Figure 4 show characteristics of Magic Formula Tire Model. We can see longitudinal force F_x and lateral force F_y in various loads F_z. Next graph show longitudinal force F_x for different values of friction coefficient. Final graph show aligning moment M_v for different values of loads F_z.

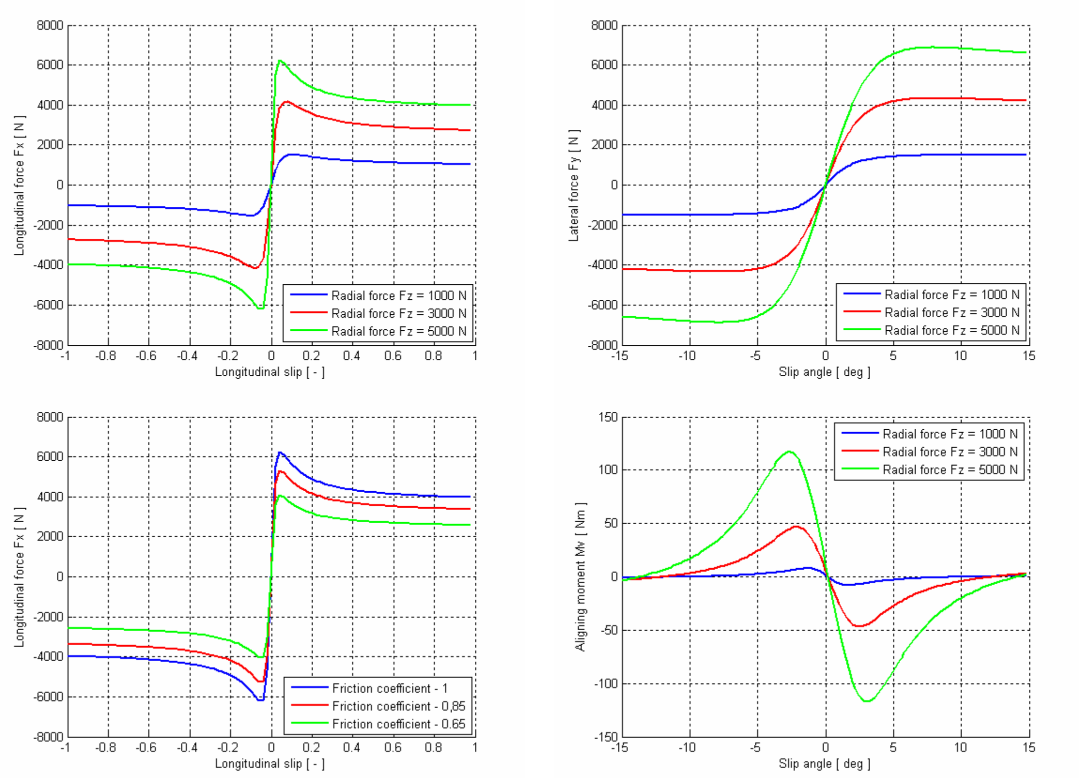

Fig. 4 Tyre force characteristics

3 VIRTUAL REALITY

The important part of the simulation model is a virtual reality. Virtual reality enables to study the behaviour of moving cars on a test track with the various surfaces. The result of simulation is presented in a 3D animation. There are several viewpoints on moving car. This method is especially useful for testing the systems for directional stabilization of vehicles.

Fig. 5 Virtual reality

4 HARDWARE-IN-THE-LOOP SIMULATION

Hardware-in-the-Loop (HIL) simulation is a test technique that helps reduce development cost and increase the quality of a vehicle. HIL simulation simulates the I/O behavior of a physical system that interfaces to an ECU in real-time.

HIL is an integrated part of the design cycle. Figure 6 below represents the design cycle of embedded control applications common to automotive, aerospace, and defense industries.

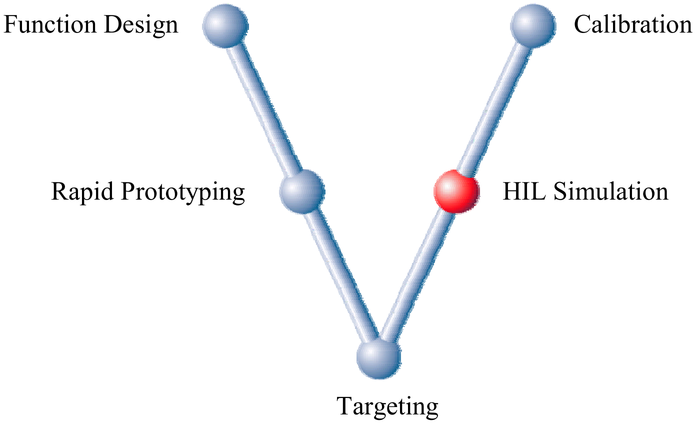

Fig. 6 Control Design Cycle

I used HIL simulation platform (dSPACE) for the test of automotive anti-lock braking systems. Mathematical model representations for each of the following subsystems in the plant simulation: vehicle dynamics (wheels, tires, roll and yaw), road characteristics, dynamics of the brake system's hydraulic components.

5 CONCLUSIONS

The contribution presents modular, flexible, 10-degrees-of-freedom model of the vehicle dynamics. It can be used "standalone" for vehicle handling performance prediction; integrated with control system algorithms; in "Hardware-in-the-loop" configurations, for testing control and diagnosis algorithms functionality. The model uses the Pacejka Magic Formulae and HSIR model for tire modelization. The forces generated in the contact between the tires and the road are of major importance for the dynamic behaviour of a road vehicle. To examine car behavior a vehicle model was built using the software MATLAB/Simulink and hardware dSPACE. The model can be used for evaluate the handling behavior of the vehicle in the normal-driving and limit maneuvers, under a variety of road conditions (dry, wet, etc.).

REFERENCES

[1] KIENCKE, U. & NIELSEN, L. *Control Systems For Engine, Driveline, and Vehicle.* 2st ed. Springer, 2005. 512 pp. ISBN 3-540-23139-0.

[2] NOSKIEVIČ, P. *Modelování a identifikace systémů.* 1st ed. Ostrava : MONTANEX a.s., 1999. 276 pp. ISBN 80-7225-030-2.

[3] VLK, F. *Dynamika motorových vozidel.* 1st ed. Brno : Nakladatelství a vydavatelství Vlk, 2000. 434 pp. ISBN 80-238-5273-6.

Reviewer: prof. Ing. Jiří Tůma, CSc., VŠB - Technical University of Ostrava