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Real-Time Vehicle Models for Simulations of Ride Comfort

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Abstract: The functional development and test of complex automotive mechatronic devices require detailed and sophisticated vehicle models that have to fulfill real-time requirements if they are to be used in hardware-in-the-loop simulations. There is an increasing demand for more detailed plant models as a basis for the development and test of complex control algorithms in ride-comfort. This paper presents a method to integrate ride-comfort characteristics into well-established real-time vehicle models as regards engine-, drivetrain- and carbody vibrations. Thus it is possible to simulate characteristics that are essential for the development and test of comfort-related automotive mechatronic devices.

Keywords: Vehicle Dynamics, Automotive Simulation Models, Real-Time Simulations, Ride-Comfort, Carbody Modes, Engine Vibrations

1. INTRODUCTION

In view of the demand for efficient vehicles, lightweight constructions and fuel-saving strategies (such as cylinder cut-offs) are becoming more and more important. However, they have a negative impact on the ride-comfort of passenger cars (Rottner 2010). Therefore mechatronic systems have been developed to compensate for this loss in ride-comfort, e.g. switchable and active engine mounts are intended to improve insulation of engine vibrations. These vibrations can be especially significant for lightweight engines or engines with cylinder cut-off strategies (Marienfeld 2006). Other mechatronic devices have been developed to damp carbody vibrations (Mahinzaeim 2007) by controlling a tuned mass. Today's commercial real-time vehicle models (such as *CarMaker*, *ASM*, *veDYNA*, etc.) for testing and developing automotive control systems are limited to the handling of vehicles, i.e. the driving behaviour. They are able to cover the overall chassis movement of a car with characteristics like lateral acceleration, yaw rate, tire forces, etc. These handling characteristics have low frequencies (Mitschke 2004, Troulis 2002, Freymann 2001) and refer to a bandwidth of 0 to 6 Hz. These models are widely used for hardware-in-the-loop simulations to test ECUs for driver assistance systems such as the ESC. To develop and to test the mechatronic devices for enhancing the ride-comfort, these typical vehicle models covering the handling behaviour of passenger cars do not go into sufficient detail. Therefore plant models are needed that are also valid for ride-comfort effects. If these models are intended to be used for hardware-in-the-loop simulations they have also to fulfil certain real-time requirements.

This paper presents a method to integrate ride-comfort characteristics into well-established vehicle models. Thus an enhanced multibody system is detailed that is able to describe ride-comfort effects and which is then implemented in the *Automotive Simulation Models* (*ASM*). The modifications are analyzed in view of their impact on the vehicle characteristics and on the computing time on a real-time platform.

2. RIDE-COMFORT CHARACTERISTICS

In this paper the considered ride-comfort effects are categorized with regard to their origin, i.e., engine, carbody, and drivetrain.

2.1 Engine

In general there are two different vibration phenomena associated with the engine of a car: the externally-excited and the self-excited vibrations. For the externally-excited vibrations, the resonance of the elastically mounted engine is matched by periodic excitations from the wheels, due to certain tire or road surfaces for example (Mitschke 2004). The vibrations resulting from the engine itself are referred to as self-excited vibrations. The cause for this kind of vibration is the acceleration and deceleration of masses as well as the periodic firing within the cylinders (Taylor 1985, Mitschke 2004). Their characteristics depend on the driving condition and on the configuration of the engine (type of engine, number of cylinders, etc.). Cylinder cut-offs or unbalanced combustions intensify the self-excited vibrations. The resonance frequency of the elastically mounted engine is about 10 to 20 Hz, but the rate of the self-excited vibrations varies in a wide range. The main excitation of the common four-cylinder inline-engine is a vibration of second order with a frequency range between nearly 20 and 200 Hz (Freymann 2001).

2.2 Carbody

The carbody is a lightweight and three-dimensional wide structure, therefore it is prone to structural vibrations (Genta 2009). The first eigenmodes of a carbody are the first bending- and the first torsion-mode. For ordinary passenger cars the frequencies of these vibrations are about 30 Hz (Freymann 2001).

2.3 Drivetrain

The torsion-elastic drivetrain is a source for different effects of discomfort (Bencker 1998), it transmits vibrations to the carbody at different spots. For the common front engine with rear wheel drive layout, the two essential devices in the transfer path are the engine in the front of the vehicle and the axle transmission located at the rear. Both devices exert vibrations and supporting torques onto the vehicle body, whereas the supporting torques cause a twisting of the carbody. The mountings of the engine and the axle transmission, i.e. hydromounts and rubber bushings, have a significant impact on the transfer of vibrations from the drivetrain onto the carbody.

3. MODELLING

3.1 Basic Principle

The basis for the development of ride-comfort vehicle models is the *ASM Vehicle Dynamics* by *dSPACE* (cf. Fig. 1).

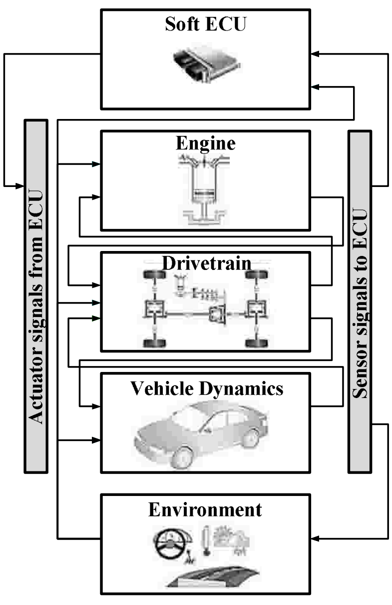

Fig. 1. Structure of the *ASM Vehicle Dynamics*, according to (Waeltermann 2009).

The models are open *MATLAB/SIMULINK* ones for describing the handling of passenger cars and consist of submodels for ECUs, the engine, the torsional-elastic drivetrain, the vehicle dynamics, and submodels for describing the environment of the car. Due to their modular design and open character, the entire vehicle models are very well suited for implementing modifications. In order to model the ride-comfort related characteristics described in Section 2, modified vehicle-dynamics models have to be integrated into the entire vehicle model, according to Fig. 1. Therefore the main aspect of the implementation of ride-comfort characteristics is the exchanging of the multibody systems within the submodel *Vehicle Dynamics*.

3.2 Methodology

The *ASM Vehicle Dynamics* are made up almost exclusively of standard *MATLAB/SIMULINK* blocks. However, such a structure is sometimes not very convenient for specific modifications. Therefore the structure of the lowest level of the submodel for the vehicle dynamics has been adapted in such a way that the equations of motion of the multibody system are embedded in a *SIMULINK* S-function (cf. Fig. 2), thus the effort for exchanging the multibody system is minimized. According to (Rill 1994) the vertical dynamics of the car is described by means of minimal coordinates within a vehicle-fixed reference frame. So the equations of motion within the S-function are of the form

$$M(q)\underline{\dot{u}} = Q(q,u) - H(q,u), \tag{1}$$

$$\underline{u}(q,\dot{q}) = K(q)\underline{\dot{q}}, \tag{2}$$

with the generalized coordinates q, the generalized velocities u, the mass matrix M, the vector of the generalized forces and torques Q, the vector of the generalized Coriolis forces and -torques H and the kinematic matrix K. The equations of motion are solved by a Cholesky algorithm at each simulation step.

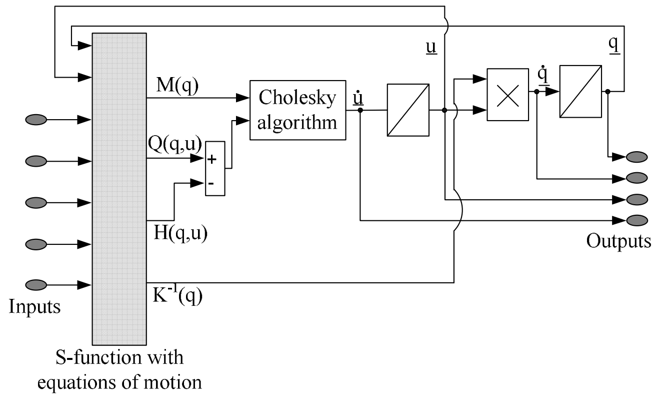

Fig. 2. S-function-based modifications within the submodel "*Vehicle Dynamics*".

Because the equations of motion are encapsulated in a *SIMULINK* S-function, the vertical dynamics of vehicles can easily be exchanged. To this effect a methodology has been developed that uses a generic modelling tool and a script