Contribution to the Integrated Control Synthesis of Road Vehicles

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***Abstract*—A nonlinear vehicle model with 22 motion degrees of freedom, used for synthesis of the system autopilot, was described in the paper. It was demonstrated how a controller can be designed on the basis of such relatively complex dynamic model, ensuring simultaneous motion stability of the vehicle in longitudinal, lateral and vertical directions, as well as the stability of roll, pitch, and yaw dynamics of the vehicle about corresponding axes. Vehicle automatic control was realized at two hierarchical levels: tactical and executional. Proposed scheme of the distributed hierarchy control enables control of entire vehicle dynamics as a multibody dynamic system. Control has been synthesized in such a way that the system satisfies set criteria of dynamic behavior. The synthesized controller improves system motion caused by action of casual, external perturbations, and internal inertial and centrifugal forces which appear as a consequence of an inadequately adapted ride velocity to the road geometry. Also, necessary information for estimation of unknown time-variant parameters of the dynamic model and of tire-road interaction were briefly given in the paper. Simulation results were presented and analyzed for one example of characteristic trajectory with perturbation of type of an uneven and slippery road, as well as a wind gust.**

***Index Terms*—Centralized control, distributed hierarchy control strategy, multibody dynamic systems, road vehicles, vehicle autopilot.**

I. Introduction

THE ROAD vehicle represents a complex, expressedly nonlinear multibody dynamic system, consisting of rigid bodies and elastic elements. Such system possesses a great number of degrees of freedom (DOF's). Some of these motions, quality of which is essential for the safety and ride comfort, need to be controlled. Others, for example elastic modes of the vehicle chassis or of the particular elements of subsystems, should not be controlled. Vehicle stability, quality of dynamic behavior and its maneuvering capabilities, predominantly depend on the system design and on the performance of its active control subsystems. The choice of the best control strategy, within the limits of a technical feasibility, represents a complex task solving which demands knowledge of the vehicle dynamic behavior in different ride conditions. For these reasons, there appears a necessity of knowing the most accurate model. However, the conventional approach to control problem solving is to adapt the model complexity to the conditions of the application of the selected control procedure. Very often the linear optimal regulator with respect to the state variables was used [1], solving the typical LQ-problem by satisfying the set performance index. This regulator, as well as similar procedures which minimize the criterion function in the frequency domain or in the space of state coordinates, use linear [1], [2] or bilinear [3] quarter car model, i.e., suspension system model. Somewhat more complex model is the half car model or single-track-model, popularly called the "bicycle model" of the vehicle [4], [5]. This model approximates the vehicle dynamics with restricted number of DOF's [6]. It describes the vehicle dynamics in the longitudinal and lateral direction of motion, the dynamics of vehicle yawing as well as rotations of the front and rear tires about their vertical axes. The common characteristic of all aforementioned simplified models is that none of them fully describes the entire vehicle dynamics, but only the dynamics in the particular motion directions. Accordingly, the controllers for longitudinal and lateral motion are synthesized separately, as well as the controller of the vertical dynamics of wheel suspension. The latter is minimizing vibrations, i.e., undesirable vertical bobbing of the vehicle due to the variation of road-surface profile. These independently synthesized controllers are then coupled into one unique control system. Our approach represents the synthesis of system controller, based on the relatively complex model of an entire road vehicle.

The purpose of this paper is to demonstrate how a relatively complex, nonlinear, complete vehicle model can be implemented for the synthesis of the dynamic control system. One such model is capable to describe the nonlinear vehicle behavior in a sufficiently broad range of its state values and its input, control variables. On the other hand, linearized models are good approximations of the system only in some relatively narrow zones of linear dependence from their state variables. Out of these zones they are just rough approximations of their real behavior. Beside that, the simplified, decoupled models lose information about the cross-section interactions of the particular values, so that they have only limited practical applicability.

By the chosen approach of the *model based control* it is understood that real-time estimation of time-variant system parameters should be ensured, as well as the estimation of the interaction parameters of the vehicle and the road surface. The algorithm for the estimation of the stated parameters is based on known equations of the system model. Which control strategy, i.e., which control scheme will be chosen, depends on the control task which has to be realized. For road vehicles, several criteria which system should satisfy during its motion

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can be established. These are: motion stability, ride quality, ride comfort, criterion of minimal suspension system deflection and tire deflection, and the criterion of high level maneuvering capabilities of the vehicle. By *motion stability* we mean the stability of the prescribed, i.e., desired vehicle trajectory and the realization of the desired chassis orientation. *Ride quality* during driving refers to the elimination of sudden, jerky changes of the lateral acceleration of the vehicle and sudden changes of the yaw rate about the vertical vehicle axis. Good quality behavior, in that sense, means continual, smooth changes of velocities and accelerations of the given state values. *Ride comfort* represents elimination of unpleasant vibrations, i.e., minimization of vehicle body heave motion relative to the road surface. *Minimal suspension system deflection* and *tire deflection* relate to the dilations (compression or extensions) of springs of shock absorbers and to the dilations of the tire pneumatics. Large deformation amplitudes raise the danger of vehicle instability or tire defects due to large dynamic loads. By *maneuvering capabilities* of vehicle we mean the technical ability of the vehicle to change the driving course in a rather broad range, quickly and easily, with minimal changes of the control magnitudes. Satisfying the nominated criteria of vehicle control depends on the equipment of the vehicle that is at our disposal. In that sense, we can speak about completely automatic controlled vehicle. Such vehicles possess active control systems,[1] sensor systems, and, more recently, a system for communication with the environment. This system ensures information about the road geometry, as well as about the exact vehicle position on the road. By semiautomatic vehicle control, the existence of some of the active control systems which correct the commands of the operator (driver) is understood. Automatic vehicle control can possess three hierarchical levels: 1) strategic control level; 2) tactical control level; and 3) executive control level. The *strategic control level* enables the controller, based on information about the terrain topography and the momentary position of the vehicle in space, to determine the desired, optimal trajectory in the presence of obstacles. By this control level the use of the vision system, telecommunication and artificial intelligence elements is understood. The *tactical control level* determines the way, i.e., the "tactics" of the realization of the prescribed vehicle trajectory and the dynamics of the relative attitude deflection of vehicle body with respect to the horizontal road surface during motion. The *executive control level* is realized by the controllers at the actuators level. Directly, they produce the control forces and torques at the driving/braking subsystems and at the active suspension system. The synthesis of vehicle control will be treated in this paper at the tactical and executive control levels exclusively.

II. Model of Vehicle Dynamics

A nonlinear vehicle model with 22 DOF's, with possibility of autonomous four-wheel driving (4WD) and four-wheel steering (4WS) was used for control synthesis, parameters estimation and simulation. This model is illustrated in Fig. 1. The mentioned model describes motion of the vehicle mass center (MC) in three coordinate directions and three rotations of the vehicle about its main axes of inertia. Also, the model describes dynamics of the vehicle suspension system (VSS) on all four wheels in the vertical direction, as well as the tire dynamics in the same direction. Each wheel possesses, beside vertical deflection, two extra DOF's: rotation about the horizontal axis with angular velocity $\omega_i,\ i = 1, \cdots, 4$, and rotation about the vertical axis with respect to the road surface. The second rotation represents a change of the ground steering angle $\delta_i,\ i = 1, \cdots, 4$. Vehicle body model is determinated by rigid body dynamics, while the model of the suspension system is described by the behavior of a mechanical oscillatory system. They are represented by their functional and symbolical schemes in Fig. 1. Tire model is determinated by a nonlinear, functional dependence between the longitudinal and lateral tire-road interaction forces, respectively, and a tire sideslip ratio, i.e., the corresponding tire side slip angle. The used vehicle model is based on the modified model by Peng and Tomizuka [7], who have used the original models by Lugner [8] and Sakai [9], [10]. The model from [7] has been structurally rearranged and extended by relations describing the vertical dynamics of tire pneumatic behavior. The mentioned model is expressed in a compact vector form, suitable for simulations and synthesis of control laws.

The defined model is valid in the case when the following assumptions can be adopted: 1) vehicle body represents a rigid body in a mechanical sense, supported by the road surface with four elastic subsystems, representing the VSS; 2) VSS possesses elastic properties only in vertical direction (perpendicular to the road surface), while it is considered that it is absolutely rigid in the longitudinal and lateral directions; and 3) deviation of the vehicle chassis position (orientation) with respect to the road surface is small due to its referent value when the vehicle is at rest. This means that approximations $\Phi \approx \sin(\Phi)$ and $\cos(\Phi) \approx 1$ are valid in case of small angles of pitch and roll; and 4) the road surface is practically horizontal, i.e., the angle of road side elevation is small (not more than a few degrees). Then the model of vehicle dynamics can be presented in the form

$$H(q)\ddot{q} + h(q, \dot{q}) = \tau + F_w(q, \dot{q}) \tag{1}$$

where the following symbols were used: $q = [x\ y\ z\ \Phi\ \theta\ \varepsilon]^T$ is a (6 × 1) vector of the global state variables, describing the position and orientation of the vehicle body MC with respect to the coordinate system fixed to the ground; x, y, z are the positions of the vehicle MC along three coordinate directions in [m]; Φ, θ, ε are the corresponding angles of roll, pitch, and yaw of the vehicle body in [rad]; $H(q)$ is a (6 × 6) inertia matrix, expressed in [kg] and [kgm^2], respectively, $h(q, \dot{q})$ is a (6 × 1) vector of gravitational and centrifugal forces acting in the vehicle MC, expressed in [N] and [Nm], respectively; τ is a (6 × 1) vector of driving forces and torques referred to the vehicle MC expressed in [N] and [Nm], respectively; $F_w(q, \dot{q})$ is a (6 × 1) vector of the external forces and torques, acting on the vehicle body during its motion along the road. Elements of this vector take into account forces and torques of tire rolling, resistance, aerodynamic resistance forces during motion, as

[1] Active suspension system, active driving/braking system, antilock braking system (ABS-system), etc.