Global Chassis Control: Integration Synergy of Brake and Suspension Control for Active Safety

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The paper deals with the investigation of integration synergy of brake and suspension control for reduction of the stopping distance. The basic idea is to take a controllable suspension and to optimize it for decrease of road-tyre force fluctuation. A nonlinear suspension control is proposed for this task. The outlined concept is implemented in a multibody simulation environment and simulation experiments verify its contribution.

Topics/A3, A5, A11

1. INTRODUCTION

The amount of traffic accidents is decreased in Germany in 2002 by 3.9 % compared to the previous year according to the statistics of the German auto club ADAC. Among other factors the advanced vehicle technology is responsible for this positive development. In order to keep it new concepts for active safety are needed.

Current vehicles are equipped with many electronic control devices assisting driver in daily and emergency situations. The devices are partially connected to each other by networks. Complexity of such control devices has significantly risen during the last decade. Road vehicles are currently true mechatronic systems due to many complicated electronic systems on board. Moreover, the development will be more and more focused on the advanced control features. According to the representatives from the automotive industry about 90 % of innovations in vehicle development are based on microprocessors and intelligent control programs.

The communication between earlier stand-alone devices is a challenge, which will bring added value not only in operational comfort of the vehicles, but particularly in active and passive safety. Several proposals for the integration of the active suspension elements exist, however there is a general problem of suitable integration of vehicle chassis control [1]. In general it is unclear whether the suitable approach is in the direction of control centralization or in the direction of coordination of decentralized control subsystems. Nevertheless the investigated case of integration of suspension control and braking where only coordination is applied can bring important improvement. It is an example of suitable coordination approach. Among the others, synergetic effects between vehicle controllable suspensions and brake systems are expected, in other words the vehicle stopping distance will be reduced if the suspension is controlled in accordance for the braking manoeuvre.

Such approach has been investigated with the simplest control integration where during braking the suspension is just switched to hard setting [2]. Such approach does not use the potential of integration synergy. In order to take advantage of it it is necessary to apply selective specially dedicated nonlinear control of the vehicle suspension.

Particularly the emergency brake manoeuvre, which is at present usually supported by brake assistant systems in order to apply maximum brake pressure, could be with the aid of optimal controlled suspension shorted. However, the optimal suspension is not the only possibility for the reduction of the stopping distance. Advanced tyre developments such as for the Continental 30 m concept of Continental or even these connected with variable tyre contact such as F400 Carving of Mercedes are other ways for the reduction of the stopping distance.

2. INTEGRATION SYNERGY OF BRAKE AND SUSPENSION CONTROL

Many vehicles particularly in higher segments are already equipped with controllable suspension and advanced brake control systems, but the control algorithms are used to be rather conservative. The controllable suspension systems are currently based on semi-active dampers.

The basic presumption for the real integration of suspension control in the active safety chain is the switching between normal operative and emergency modes. In the operative mode the vehicle suspension will be controlled with comfort objectives. In the emergency mode the specialized optimized algorithms for suspension will be applied. Emergency braking is one of the manoeuvres, which require such advanced algorithms, which exploit the whole potential of the vehicle controllable suspension.

2.1 Concept of Brake-Friendly Suspension

Tyres play an important role in the emergency braking manoeuvre being an interface between a vehicle and a road. However, this coupling is rather nonlinear and depends on many parameters. Generally it can be stated that the fluctuation of vertical tyre forces has an influence on the braking distance, since the friction coefficient between tyre and certain given road depends on the vertical load F_z and the longitudinal slip κ: $\mu = \mu(F_z,\kappa)$. As a result of this nonlinearity, the oscillations of the vertical force result in an extension of the stopping distance.

Besides that the controlled suspension is in any case capable to decrease the situation of loosing contact between tyre and road (vehicle jump) when the braking is completely interrupted. These undesirable situations are even worse in case of ABS. ABS algorithm is avoiding wheel blocking that is exactly happening after losing contact tyre-road. The consequence of ABS algorithm and its sampling time is that after losing and again gaining the contact the vehicle is for some time interval not being braked**.**

Current vehicle suspension systems are designed to satisfy a trade-off between road handling and comfort. Since the passive design has been almost driven to its limits active and semi-active systems can increase the performance. Low energy demands as well as fail-safe features are good arguments for the semi-active systems.

A dynamically controlled vehicle suspension, which controller is optimized to the braking manoeuvre, can suppress the undesirable vibrations and shorten the braking distance. This is called brake-friendly suspension. The main goal during the stopping manoeuvre is to reduce the fluctuation of the vertical forces between road and tyre. This is the control objective to be provided.

2.2 Semi-Active and Limited Active Suspension

The most often current version of controlled suspension is the semi-active one [3]. Its principle is that it can only dissipate energy, thus its force-velocity diagram is on Fig. 1a. The fully active suspension is certainly an excellent option; however, the energy consumption is rather high. Its force-velocity diagram is on Fig. 1b. The so-called limited active suspension [4] seems to be a feasible compromise between fully active and semi-active suspension also regarding the decrease of the stopping distance. Its force-velocity diagram is on Fig. 1c. This concept use actuators, which can generate forces with limited energetic demands. Electric linear drives could be a new technology for such passenger car suspensions, because of dynamic response, energy regeneration, [4].

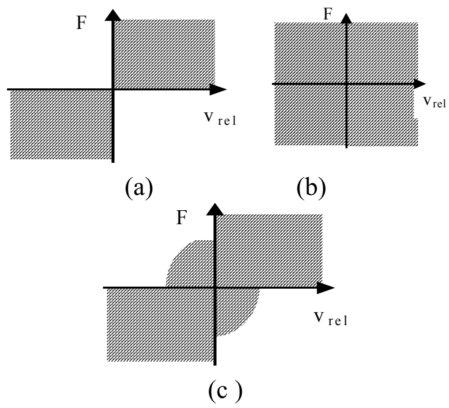


Fig. 1 Semi-active, active and limited active suspension

3. MOPO DESIGN METHODOLOGY

The vehicle system to be controlled is usually significantly nonlinear. Thus the traditional control design approaches based on linear models provides only limited results. Therefore an advanced methodology for the control design in case of semi-active vehicle suspensions has been developed [3, 5, 13], which can also be considered as a methodology for the design of mechatronic systems for vehicles in general.

The state-of-the-art of traditional design methodology of controlled vehicle suspensions has been based on restricted design models, linear control laws based on linear design models and limited experimental verification replaced usually with only experimental parameter tuning. On the contrary the advanced design methodology is based on the full usage of realistic design and reference simulation models (taking into account the essential nonlinearities and important degrees of freedom) and on the control design taking into account the significant nonlinearities of the controlled plant.

The other problem arising from the nonlinear nature of models and/or control laws is the design procedure of control law. The current direct synthesis methods of control of nonlinear systems are limited by many necessary additional conditions of the controlled plant [6]. There is only one new approach for control synthesis with realistic requirements on the nonlinear plant [7]. Nevertheless the control design with minimal requirements on the nonlinear plant that is combined with the new advanced control design methodology is the MOPO approach.

The main steps of new MOPO design methodology are following:

Models: There is developed the reference simulation model of the plant to be controlled (vehicle suspension system). It is as detailed as possible in order to cover the dynamical phenomena to be controlled. Besides this reference model there is developed also the design model. It is simpler than reference model but it includes all essential features (DOFs, nonlinearities etc.).

Control law selection: Based on the design model the physical insight into the plant to be controlled is developed. Using this physical insight a suitable control law is proposed. It usually includes parameters to be designed for appropriate function of controlled plant.

Control law design: The control law is parametrized. The parameters are determined by the MOPO (Multiple Objective Parameter Optimization) approach. A performance index usually in the integral form is selected. Important and representative excitation inputs are taken. The design simulation model is integrated with these inputs and the performance index is evaluated. Then the performance index is just a function of the unknown control law parameters. They are determined by its optimisation. It is design-by-simulation and design-by-optimisation.

Verification: First the reference model is verified by comparison with experiments on real plant. Second the design model is verified against the reference model. Then the designed control law is verified by the simulation of the reference model also using larger set of input excitations. Finally the resulting control law is verified by experiments on real plant.

4. VEHICLE MODEL

The whole concept is verified in two phases. Firstly, the potential of the shortening the braking distance is verified on a simple vehicle model and a starting set of controller parameters is determined. Secondly, the concept is implemented to a 3D vehicle model (see Fig. 2) and the results are evaluated for road surfaces of different profiles, such as smooth profile, deterministic sinusoidal profile or stochastic excitation representing diverse qualities of the road profiles. Within this procedure the whole range of different control concepts have been investigated.

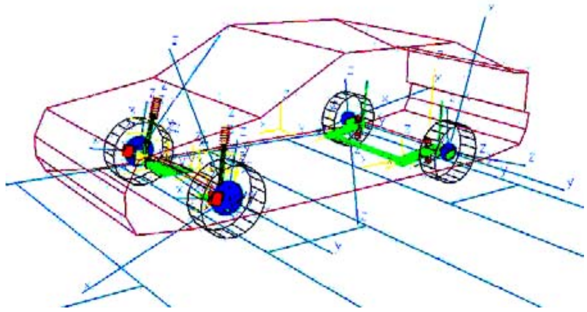


Fig. 2 Multibody vehicle model**.**

The vehicle models are equipped with several suspension types. The reference model has passive suspension and the controlled models have either semi-active dampers or limited active actuators. The brake circuit is extended with an anti-lock controller based on an ABS algorithm from [8].

The 3D vehicle is designed in a multibody package SIMPACK; however, the controller of semi-active dampers as well as the anti lock algorithm is implemented in a control engineering tool MATLAB/Simulink. The both software packages are connected by means of co-simulation based on inter-process communication, [3]10]. Since the anti locking controller induces significant frequencies to the system, one must pay attention to selection of proper tyre models, [9].

5. SUSPENSION CONTROL

The control objective is to reduce the fluctuation of the road-tyre forces. The selected control algorithm is based on the so-called nonlinear extended groundhook suspension [11, 12, 13]. This control concepts is based on virtual suspension damping elements b_1 and b_2 (Fig. 3a), which virtual forces are then applied by the actuator (Fig. 3b).

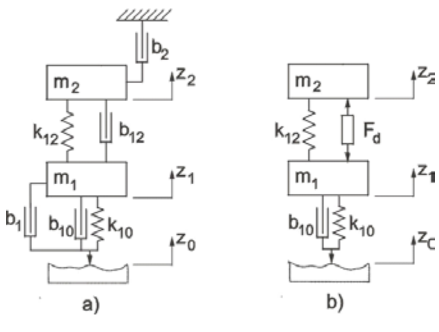


Fig. 3 Extended groundhook.

The desired force F_d of the extended groundhook depends further on virtual springs Δk_{10} and Δk_{12} and virtual damper b_{12}:

$$F_d = b_1(\dot{z}_1 - \dot{z}_0) - b_2\dot{z}_2 - b_{12}(\dot{z}_2 - \dot{z}_1) + \Delta k_{10}(z_1 - z_0) - \Delta k_{12}(z_2 - z_1). \quad (1)$$

The parameters b_1, b_2, b_{12}, Δk_{10} and Δk_{12} can be either constant (linear control law) or state-dependent (nonlinear control law) [12, 13]. Because of nonlinearity of the actuators, the state-dependent parameters b_1, b_2, b_{12} provides better performance.

The performance index is the fluctuation of road-tyre forces described by:

$$J = \int_0^{Tlarge} F_{10}^2 dt \quad (2)$$

where F_{10} is the road-tyre force. The direct evaluation of stopping distance as performance index has been also applied.

5. INFLUENCE OF ACTUATOR DYNAMICS

During the simulation [13] and real experiments [15] with the control of vehicle suspension it has been realized that the dynamics of suspension actuator plays very important role in the achieving advanced values of performance index.

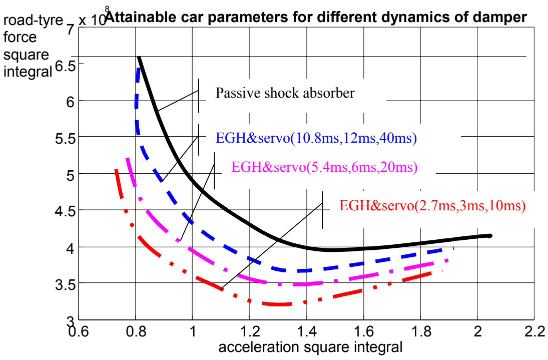


Fig. 4 Comparison of Pareto sets for different shock absorber dynamics (triple of parameters: time delay of damper response [ms], time constant for decreasing force [ms], time constant for increasing force [ms])

This can be demonstrated [14] on the accessible Pareto boundary of relationship between road-tyre forces and sprung mass accelerations according to different damper dynamics (Fig. 4) and on the accessible time behaviour of road-tyre forces (Fig. 5).

This experience has lead naturally to the investigation of different possible concepts of controllable damper (shock absorber). The traditional implementation of controllable damper (Fig. 5a) is the hydraulic damper with controllable orifice in the bypass. Such device can achieve settling time above about 10 ms. Another version of hydraulic damper however with magnetorheologic control of bypass flow can achieve settling time between 5 and 10 ms.

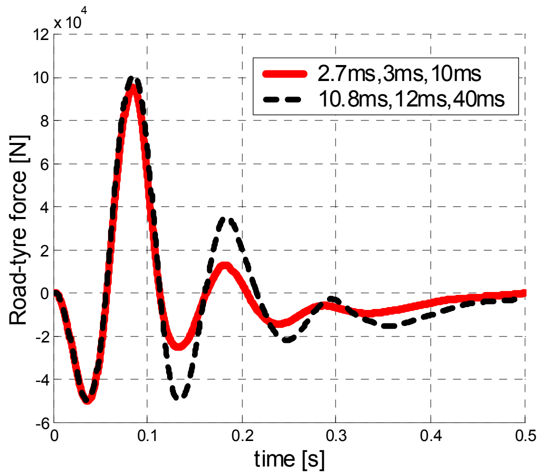
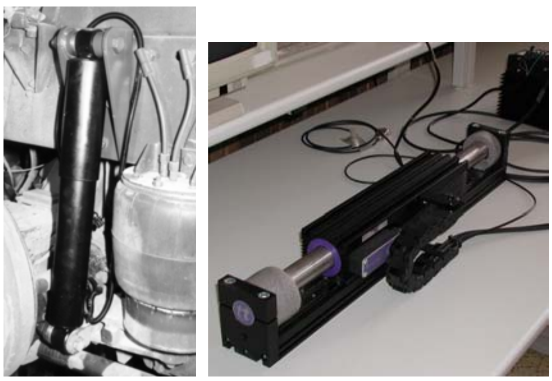


Fig. 5 Comparison of time response of semi-active suspension to bump different shock absorber dynamics

The completely new and very promising principle of controllable damper is the electric linear drive (Fig. 5b). Such device can achieve settling time about 1 ms and can be operated as a semi-active device with interesting energy recuperation function and also as an active device. Such new damper is currently feasible only for passenger cars according to the ratio damping force / geometric size.



(a) (b)

Fig. 5 Hydraulical and electrical damper

The other important property of controllable damper that influences the resulting suspension behaviour is the symmetry of damper characteristics. The passive shock absorbers are asymmetric because of passenger control. The effects of controlled shock absorber can be increased by symmetry of characteristics because the extent of damping forces is increased.

All these properties are investigated as different cases in the simulation experiments.

6. SIMULATION EXPERIMENTS

The simulation experiments evaluate three passive dampers, which have standard (commercial) characteristic and characteristic softer and harder than commercial. It would represent also the so-called adaptive suspension systems, which switch between hard, middle and soft characteristic according to the global vehicle states, such as velocity and brake pedal position.

Further simulations have been performed with the semi-active models of different configuration. The semi-active dampers have non-symmetric and symmetric characteristics and different time constants. The symmetric characteristic of the semi-active dampers enables better range of the forces to be applied.

The time constants representing the electrical dynamic behaviour of semi-active dampers are a significant performance restriction. The semi-active dampers are usually feedthrough controlled by electrical current. The time constant results not only from the eigendynamics of the coil controlling the orifice in the damper, but also from the dynamics of the current source for the current feedthrough control. Besides using electronics with better performance for the feedforward control, the feedback force control of the semi-active damper is proposed, [14]. The feedback force control requires a force sensor on the damper to get the actual force, which is then compared with the force defined by the input current. This feedback control has potential to improve the performance of the semi-active damper significantly, because the reaction times of the damper are approximately one order of magnitude better then with the original electronics and feedforward control. The simulation experiments has been performed with time constants 10 ms for increasing current and 20 ms for decreasing current, which represent a semi-active damper with a realistic dynamics.

Table 1 Simulation results on good stochastic road.

Damping concept	Brake distance [m]
Soft passive	46,22
Commercial passive	48,18
Hard passive	48,12
Semiactive nonsym 10/20ms	45,53
Semiactive sym 10/20ms	43,25
Semiactive nonsym 1ms	43,43
Semiactive sym 1ms	42,71
Limited active 1ms, 1500 N	41,85

The vehicle has initial velocity of 100 km/h. The emergency braking manoeuvre is simulated on a road excitation representing a good stochastic road. The simulation results presented in Table 1 and Fig. 6 indicate a shortening of the vehicle stopping distance by 2.5 to 6.3 meters. Besides the influence of the symmetric characteristics of the semi-active damper, the contribution of the reduced time constant is observable. The limited active concept brings further reduction of the stopping distance by 0.8 m compared to the best semi-active concept.

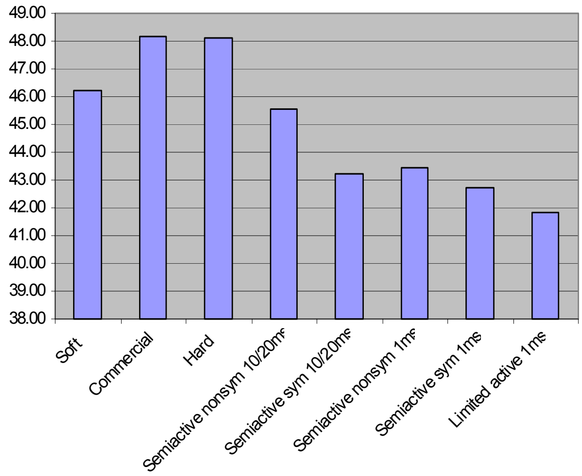


Fig. 6 The stopping distance for different suspension concepts on good stochastic road.

7. CONCLUSIONS AND OUTLOOK

The paper presented a concept of integration of brake and suspension control for reduction of the stopping distance. This concept is based on the optimisation of the suspension control developed for decreasing the tyre force fluctuation with the objective to reduce the stopping distance. In order to control the nonlinear semi-active dampers a nonlinear control law is proposed.

The simulation results indicate a significant shortening of the stopping distance from 100 km/h by up to 6.3 meters for the given model and simulation scenario, which represent shortening by up to 13 %. This concept seems to be able to increase the active safety of vehicles with feasible demands on their modifications and additional costs.

This concept is almost instantly feasible for high-class passenger cars, which are equipped with semi-active dampers. Since the concept offers a combination of functionality for active safety and ride comfort, it can accelerate the transfer of the technology to the middle class.

The communication between brakes and suspension is not proposed just for the passenger cars, but the same concept is also feasible for trucks. The improvement of truck braking capabilities is important safety criterion for all road transportation participants.

The similar concept is being developed for the ASR, i.e. for the control of the slip during acceleration and stability control ESP. Equally to the braking, the efficiency of ASR and ESP can be supported by improved contact of tyre with the road and in this way the controllable suspension with advance nonlinear control is able to contribute to the active safety of vehicles.

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