Automotive Suspension Systems

Motivation for the Study of Mechanical System Physical & Mathematical Modeling

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State of the Art: Suspension Systems

• **Introduction**
  – The vehicle suspension system is responsible for **driving comfort and safety** as the suspension carries the vehicle body and transmits all forces between the body and the road.
  – In order to positively influence these properties, semi-active and/or active components are introduced. These enable the suspension system to adapt to various driving conditions.
  – By adding a variable damper and/or spring, driving comfort and safety are considerably improved compared to suspension setups with fixed properties.
- This strategy requires that the control behavior of these components is known and that laws on how to adapt the free parameters depending on the driving excitations are known.

- This also requires the identification and fault detection of the involved components resulting in a mechatronic design.

**Vehicle Suspension System**

- The vehicle suspension system consists of wishbones, the spring, and the shock absorber to transmit and also filter all forces between the body and road.

- The spring carries the body mass and isolates the body from road disturbances and thus contributes to drive comfort.
The damper contributes to both driving safety and comfort. Its task is the damping of body and wheel oscillations, where the avoidance of wheel oscillations directly refers to drive safety, as a non-bouncing wheel is the condition for transferring road-contact forces.

One-Dimensional Vertical Vehicle Representation: The Quarter-Car Model
– **Driving Safety**
  
  • Driving safety is the result of a harmonious suspension design in terms of wheel suspension, springing, steering, and braking, and is reflected in an optimal dynamic behavior of the vehicle. Tire load variation is an indicator for the road contact and can be used for determining a quantitative value for safety.

– **Driving Comfort**
  
  • Driving comfort results from keeping the physiological stress that the vehicle occupants are subjected to by vibrations, noise, and climatic conditions down to as low a level as possible. The acceleration of the body is an obvious quantity for the motion and vibration of the car body and can be used for determining a quantitative value for driving comfort.
Frequency Response Magnitude for Normalized Body Acceleration and Tire Load for a Passive Suspension System
– In order to improve the ride quality, it is necessary to isolate the body, also called the sprung mass, from the road disturbances and to decrease the resonance peak of the sprung mass near 1 Hz, which is known to be a sensitive frequency to the human body.

– In order to improve the ride stability, it is important to keep the tire in contact with the road surface and therefore to decrease the resonance peak near 10 Hz, which is the resonance frequency of the wheel, also called the unsprung mass.

– For a given suspension spring, the better isolation of the sprung mass from road disturbances can be achieved with a soft damping by allowing a larger suspension deflection.
– However, better road contact can be achieved with a hard damping preventing unnecessary suspension deflections.

– Therefore, the ride quality and the drive stability are two conflicting criteria, as shown below.
As can be seen from the diagram, the fixed setting of a passive suspension system is always a compromise between comfort and safety for any given input set of road conditions and a specific stress.

Semi-active / active suspension systems try to solve or at least reduce this conflict.

The mechanism of semi-active suspension systems is the adaptation of the damping and/or stiffness of the spring to the actual demands.

Active suspension systems in contrast provide an extra force input in addition to possible existing passive systems and therefore need much more energy.
– The figure also clarifies the dependency of a vehicle suspension setup on parameter changes as a result of temperature, deflection, and wear and tear. These changes must be taken into account when designing a controller for an active or semi-active suspension to avoid unnecessary performance loss.

– In order to prevent this, a robust or an adaptive controller has to be implemented. The adaptive controller results in a parameter-adaptive suspension system that refers to a control system which adapts its behavior to the changing settings of the system to be controlled and its signals.
– Suspension systems are classified as passive, semi-active, active and various in-between systems.
– Typical features are the required energy and the characteristic frequency of the actuator.

Comparison
Passive, Adaptive, Semi-Active, and Active Systems
– This diagram points out the conflict that automotive manufacturers face in their endeavor to improve drive safety and comfort as high-performing suspension systems can only be achieved by high-energy demand and mostly expansive and complex actuation systems.
• **Electromagnetic Linear Actuators in Suspension Systems**
  
  – The use of electromagnetic linear actuators in automobile suspensions is under development.
  
  – The reliability of electrical drives and the unconstrained integration with electronic control systems are factors that justify their use.
  
  – Rotational electromagnetic actuators have been proposed, however, their use requires a gearbox to convert the rotational movement into linear movement and to increase the force value. Linear actuators do not require a gearbox.
The main objective of ground vehicle suspension systems is to isolate the vehicle body from road irregularities in order to maximize passenger ride comfort and to produce continuous road-wheel contact, improving the vehicle handling quality.

Today, three types of vehicle suspensions are used: passive, semi-active, and active. All systems implemented in automobiles today are based on hydraulic or pneumatic operation. However, these solutions do not satisfactorily solve the vehicle oscillation problem, or they are very expensive and increase the vehicle’s energy consumption.

Significant improvement of suspension performance is achieved by active systems, however, they are expensive and complex.
Hydraulic Single-Wheel Active Suspension System

Control System \rightarrow Power Electronics \rightarrow Low-Power Electromagnetic Actuator

Hydraulic Actuator \rightarrow Hydraulic Valve

Sensors and Instrumentation \rightarrow Single-Wheel Suspension

Vehicle Engine \rightarrow Hydraulic Pump and Power supply

Other Wheels Suspension Systems
Electromagnetic Single-Wheel Active Suspension System

Control System → Power Electronics → Electromagnetic Actuator → One-Wheel Suspension → Battery

Sensors and Instrumentation → Electromagnetic Actuator

Vehicle Engine/Generator → Other Wheels Suspension Systems

Electromagnetic Single-Wheel Automobile Active Suspension

Automotive Suspension Systems

K. Craig
Model of a Hydraulic Single-Wheel Active Suspension

Model of a Electromagnetic Single-Wheel Automobile Active Suspension
Electromagnetic Active Suspension Control System
Mechatronics development and validation move indoors

The growing complexity, integration, and need to directly characterize the mechanical, software, and electronic interactions of mechatronics systems is creating demand for physical test systems that provide a more efficient means of mechatronics development and validation (MDV). By providing engineers with the tools to move mechatronics testing from the proving ground to the test lab, OEMs and suppliers will have a much more precise, safe, affordable, and repeatable means of evaluating component and vehicle performance. An example of one of these test systems is the proof-of-concept MDV bench MTS Systems demonstrated with its model-based simulation partner, dSPACE. The test bench, which integrates an active real quarter suspension with a real-time vehicle dynamics model, is designed to create realistic and repeatable maneuvers for direct characterization and measurement of vehicle dynamic events. For the first time, OEMs and suppliers will have an accurate, repeatable, and highly efficient means of evaluating active component performance by using MDV testing techniques, at both the subsystem and full-vehicle levels.
TRW active front steer helps tackle curves

A vehicle that possesses agility and handles corners and S-curves with ease attracts the attention of driving enthusiasts, so perfecting a steering technology that can provide a vehicle with nimble handling merits attention.

“All major steering system suppliers have demonstrated their own technical solutions in various test vehicles,” said Peter Heltzer, Chief Engineer of Advanced Steering Research and Development for TRW Automotive, noting that vehicles equipped with active front steer were launched by a Japanese automaker in 2002 and a European automaker in 2003.

TRW engineers have completed a concept development project for active front steer also known as steering angle overlay. The technology consists of hardware components (summing gearbox, electric motor, steering wheel angle sensor, output shaft angle sensor, and electronic control unit) as well as control algorithms to provide the desired steering functions such as vehicle-speed-dependent ratio and the fault monitoring algorithms to provide system integrity.

“Active front steer is a technology which allows electronically controlled steering inputs to be added to the driver’s steering input,” according to Heltzer. “The most important feature of active front steer is the modulation of the steering ratio between steering wheel and road wheels as a function of vehicle speed. The modulation of the steering ratio provides responsive vehicle handling at low and medium vehicle speeds and stable vehicle handling at high speeds.”

The active front steer’s summing gear has two inputs and one output. The first input connects to the steering wheel and the second input connects to an electronically controlled electric motor. The output gear’s output connects to the rack-and-pinion power steering. A planetary gearbox is the traditional solution for a summing gear, but TRW is using an epicyclic gearbox.

“In the case of an electronic failure in the active front steer system, the electric motor is automatically blocked by a solenoid-operated brake,” noted Heltzer. “In this case, the second input to the summing gear becomes zero, causing the summing gear to behave like a fixed gear ratio transmission between the steering wheel and power steering. The existence of the mechanical transmission—in case of an electronics failure—is a significant advantage of active front steer as compared to steer-by-wire.”

“The major challenge in developing active front steer is the design of the summing gearbox. Zero backlash, low friction, and low noise are the main development targets beside the reduction of package space, weight, and cost. The epicyclic gearbox provides some conceptual advantages in this regard,” noted Heltzer.

TRW’s active front steer technology was first demonstrated to customers during the 2005-06 winter at the TRW test track in Arvidsjaur, Sweden. Active front steer is applicable to front-, rear-, and all-wheel-drive vehicle applications. The technology can be an add-on to conventional power steering systems, providing new steering functions such as vehicle-speed-dependent steering ratio and enabling enhancement of the vehicle’s stability control system. “The future utilization of active front steer as part of a collision mitigation system is still under research,” said Heltzer.

K. Craig
ZF Sachs goes mainstream with active damping

Just as other advanced technologies have taken root in more mainstream vehicles after initial application in luxury and sports car segments, so too has ZF Sachs’ electronic continuous damping control (CDC) system. The new Opel Astra, which went on sale this past spring, is the first high-volume vehicle to feature the technology, an application that will help to increase the total number of CDC-equipped vehicles on the road to about 225,000 in 2005, according to Michael Hankel, Member of the Board of Management for ZF Sachs’ Suspension Division. When the technology was launched in 2001 as optional equipment on cars such as the BMW 7 Series and Ferrari Modena, only about 10,000 units featured CDC.

Though the highest penetration will continue to be in Europe, Hankel believes the North American market holds a lot of promise for CDC, particularly in SUVs. The technology could help to prevent roll overs, he said, by reducing body lean during cornering and sudden avoidance maneuvers. China is another potential market for the system, Hankel said.

The variable damping system is equipped with a “variable size” proportional valve that continuously controls the rate of damping—depending on the valve setting, the orifice for the oil flow is widened for soft damping characteristics or narrowed for hard damping characteristics. The damping force is individually controlled at all four wheels to help keep the vehicle body as stable as possible while driving on uneven surfaces or cornering at high speeds, which was certainly the case while driving a CDC-equipped Astra on the track at the Automotive Testing Papenburg Proving Ground in Germany.

In the Astra, two modes (comfort and sport) can be selected to modify the driving behavior of the car. Regardless of the selected setting, the system will interject to make any necessary adjustments in emergency situations.

Because of different demands for the installation space of telescopic damper assemblies, two different CDC damper designs are available. The CDC damper has an integrated proportional valve that is an integral element of the slave or displacing piston. The CDC damper, which is the type used in the Astra, has a proportional valve that is located externally at the bypass of the displacement unit. With current absorption from 0 (firm damping) to 1.6 A (soft) for the internal CDC valve and 0 to 1.6 A for the external valve, the system features low power consumption—15 W nominal in controlled operation.

Every two milliseconds, the system’s electronic control unit (ECU) recalculates the current needed for the present damping power requirements and passes this value onto the damping valves. The calculations are based on data provided by five acceleration sensors: three body sensors that measure roll, pitch, and heave, and two wheel sensors that measure road surface conditions. The ECU also considers data inputs provided by the vehicle’s CAN bus—such as engine torque,
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AUTOS ON MONDAY | TECHNOLOGY

A Curious Fluid and an Electric Jolt Deliver a Magic Carpet Ride

By JIM McCRAW

If you can remember back to grade-school science class, you may recall the amazement of seeing what a horseshoe magnet does to a pile of iron filings, arranging the powder in orderly patterns and holding it neatly in place.

That is a fair approximation of what happens inside the shock absorbers of some recent cars from General Motors, including the Buick Lucerne, Chevrolet Corvette and several Cadillacs.

As in most suspension systems, the shock absorbers of these cars control the motion of the wheels by forcing fluid through a series of internal passages. But rather than depending on specially calibrated valves to regulate the fluid flow for varying road conditions, GM's system uses a peculiar substance called magnetorheological fluid that transforms from a free-flowing liquid to a thick syrup in the presence of a magnetic field.

GM did not build the system it calls Magnetic Ride Control to demonstrate its Mr. Wizard cleverness. Instead, the shock absorbers were developed with Delphi, a major parts supplier, to minimize one of the most troublesome trade-offs in the engineering of a new car - the compromise between ride comfort and cornering ability.

GM says it is the industry's fastest-acting suspension, able to fine-tune its settings in a thousandth of a second, or about once every inch at 60 miles an hour. The system continuously adjusts the shock's resistance to up and down movements, maintaining a soft setting on smooth roads for a comfortable ride but stiffening the action when needed to control wheel movement or limit body lean.

The secret sauce inside the shock absorbers or suspension struts is a silicone-based fluid that contains iron spheres ranging from 3 microns to 10 microns in diameter. (A human hair is about 100 microns in diameter.) The liquid becomes very thick when surrounded by a magnetic field -- its viscosity can change from that of thin oil to a peanut butter consistency. Delphi says - and increases resistance to the shock absorber piston that moves up and down as the wheel encounters bumps.
The change from a free-flowing liquid to a soupy goop is carried out by rearranging the iron spheres suspended in the fluid. When no magnetic field is present, the spheres are randomly dispersed, but when the current is applied to electromagnets inside the shock absorber, the spheres line up, following the magnetic field just as iron filings do at the north and south poles of a horseshoe magnet. The magnetic force attracting the spheres to each other gives the fluid its molasses consistency.

The ride system uses electronic position sensors at each wheel to measure how far the wheels move up and down relative to the car body. A smooth surface causes little wheel motion, but when a larger or faster motion is detected, it is counteracted with electric current dealt out by the system's central processor — up to five amperes of current to make the fluid more resistant to flow and stiffen the shock's action.

The system's computer also receives input from sensors that monitor the car's direction of travel and the steering wheel angle, and from the antilock brakes and traction control.

Using this data, the computer is able to signal the suspension not only how much damping force is required for the road conditions, but also to control body lean when cornering and to prevent the front end from diving under hard braking. Overall, the design goal of the system is to maximize the amount of tire tread in contact with the road, which benefits handling and safety.

The magnetorheological fluid is produced by the Lord Corporation of Cary, N.C. Lord's technology is also used to damp the up-and-down motions in the driver's seats of tractor-trailer trucks and in artificial limbs, but only G.M. is using it in automotive shock absorbers.

The first production car to use this suspension system was the 2002 Cadillac Seville STS, and the next year it was standard equipment on the 50th anniversary edition of the Corvette. Cadillac's XLR roadster uses the technology and the SRX crossover wagon offers it as an option; in neither case can the driver adjust the setting. The '05 Corvette and Cadillac STS have driver-selectable suspension settings for touring and sport driving modes.

On all but the $75,000 XLR, magnetic ride is an option, costing $1,695 on the Corvette and between $6,920 and $13,000 on the Cadillacs, bundled with a long list of other options and not available separately.
The ride system offers a much wider range of soft-to-hard damping than conventional shock absorbers, and better control of vehicle motions for a flat ride and precise handling, said Jim Mero, a suspension engineer at G.M. who led the team that engineered both the Cadillac and Corvette systems. He also said that the shock absorbers were so sturdy and simple that they should last the life of the car.

Mr. Mero says this technology allows G.M.'s ride and handling engineers developing vehicles to fine tune the software instructions that control the shock absorbers at the keyboard of a computer. They can then program the ride and handling characteristics more precisely.

To demonstrate the abilities of the magnetic ride system, G.M. arranged a drive of several vehicles at its proving grounds in Milford, Mich., about 40 miles northwest of Detroit. A 2005 Cadillac STS with conventional shock absorbers, driven to establish a baseline for later comparisons, rode quite well over the entire, horribly bumpy test course at speeds up to about 45 miles an hour. Faster than that, the ride was very harsh and noisy - especially at the Big Bump, a deep pothole the length of a Chevy Suburban.

An STS sedan with the magnetic ride system set to the touring setting negotiated the entire course at speeds over 60 m.p.h., with little sensation of roughness at the steering wheel and little harshness coming up from the tires.

Switching out of the luxury cars and into a pair of low-slung Corvettes showed similar advantages for the system in a sports car. The Corvette with magnetic ride control was easy to drive over the same course at speeds nearing 85 m.p.h., including the Big Bump.

Finally, Mr. Mero rolled out an ominously-looking all-black SRX, and with a wry smile said, "Now try this one." The tall SRX, equipped with a prototype of the ride system's next generation, was stable, quiet and comfortable around the entire course - at speeds nudging 100 m.p.h.

Delphi and G.M. are reluctant to talk about specific applications for the magnetic fluid in future products, but hint that it has the potential to be useful in clutches and vibration-absorbing engine mounts.
BMW's Dynamic Drive: An Active Stabilizer Bar System

BMW has developed an active stabilizer bar system called Dynamic Drive. The system was originally launched in the 7-series in 2001 and was subsequently refined and adopted for the more recent 5- and 6-series. Dynamic Drive significantly reduces roll angle during cornering. Under normal driving conditions with lateral accelerations up to 3 m/s² for the 7 series and up to 5 m/s² for the 5 and 6 series, the roll angle is largely eliminated as depicted in Figure 1. For higher lateral accelerations, the roll angle increases gradually at the same rate as in conventional cars to alert the driver to the proximity of the stability limit. In addition, the self-steering properties of the vehicle, including understeering and oversteering, improve handling, agility, steering precision, and safety.

The self-steering characteristics of a vehicle concern the steering angle required to achieve a desired lateral acceleration. This ratio increases with increasing lateral acceleration for an understeered vehicle, in which a larger steering angle is required at high lateral accelerations than at low lateral accelerations. Since this behavior is safe and easy to handle for all drivers, all passenger cars exhibit understeering. In contrast, oversteer vehicles, such as race cars, are more sensitive at higher lateral accelerations and can generally be handled only by experienced drivers.

In vehicles with passive stabilizer bars, the self-steering characteristics are fixed by the car's mechanical parameters for all driving speeds and driving situations; relevant parameters include the spring stiffnesses of the stabilizer bars in the front and rear axles. In contrast, Dynamic Drive dynamically adjusts the self-steering characteristics as a function of vehicle speed and driving conditions, resulting in improved handling, agility, and steering precision (see Figure 2).

Dynamic Drive also eliminates a negative side effect of passive stabilizer bars, namely, the copying effect. Specifically, passive stabilizer bars transfer vertical forces from one side...
of the vehicle suspension to the other. For example, when the right-hand side of the vehicle passes over a bump, a portion of the suspension bounce force is transferred to the left side of the suspension, causing the vehicle to roll to the left, thereby “copying” the bump. During straight-line driving, Dynamic Drive decouples the two sides of the stabilizer bar and allows the wheels on each side to bounce independently, thus reducing the roll of the vehicle caused by the bump and increasing ride comfort.

The Dynamic Drive system consists of a hydraulic valve block with integrated sensors, a hydraulic pump coupled to the power steering pump, a lateral acceleration sensor, a control unit, several hydraulic lines, and two active stabilizer bars with rotating hydraulic actuators. These active stabilizers apply the hydraulic pressure to the stabilizer bar to obtain a stabilizing torque, which counteracts the roll motion of the vehicle. The hydraulic valve block consists of two pressure control valves and a directional valve for left or right cornering. Figure 3 illustrates the components of the Dynamic Drive control system.

The main control inputs for the Dynamic Drive system are steering angle and lateral acceleration. A dynamic observer implemented in the electronic control unit (ECU) calculates the necessary vehicle stabilizing torque based on a prediction derived from the steering angle signal and the lateral acceleration.

Depending on the driving situation, the vehicle stabilizing torque is distributed to the front and rear axles for ideal self-steering properties. Additional signals from the controller area network (CAN) are used for plausibility checks to ensure safety and increase system availability. The sampling rate of the system is 100 Hz.

The controller software was designed for modularity to ensure manageability of its complex functional structure. This structure consists of several main blocks for signal processing and plausibility checks, observing the lateral vehicle dynamics, calculating the commanded stabilizing torques, controlling the actuators, and monitoring safety. The underlying control principles were chosen for robustness to widely varying environmental conditions such as road friction. Special design methods such as valve operation maps and variable linearized controllers were required to cope with the strongly nonlinear behavior of the hydraulic actuator system. Multiple fallback levels within the safety.

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ADAMS Car

Integrated Application of Multibody Simulation in the Product-Development Process

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June 2001
Abstract

Global competition in the automotive industry results in increased efforts to shorten development cycles while increasing the level of quality, maintaining costs in line with market requirements and accommodating a growing variety of new models. An essential step towards meeting this challenge is the integration of computer-aided (CA) technologies and methods in the product-development process thereby leading to increased efficiency.

Multibody Simulation using the specialized ADAMS/Car simulation software plays a key role with increasing importance in the vehicle-development process at Audi, particularly in chassis development. The application of standardized computer-aided engineering (CAE) methods is based on a definition of input and output data at a certain prediction quality. Virtual checks through standardized analyses essentially contribute to milestone decisions during the product-development process, above all in the concept-development phase. During the production-vehicle engineering phase co-experimental simulation supports the vehicle tuning process.

The paper gives an overview of the major fields of application of ADAMS/Car at Audi integrated in the virtual product-development process - from elastokinematic suspension design, vehicle handling dynamics, powertrain and driveline dynamics up to durability and ride comfort. Audi-specific functionality has been implemented in ADAMS/Car for elastokinematic suspension analyses and vehicle handling simulation through customization, which also allows a rating of suspension and vehicle behavior at specific driving maneuvers. Simulation of driveline dynamics and determination of engine movement envelopes at critical driving conditions make another application focus. Full vehicle simulations on test tracks provide dynamic loads on a virtual basis for durability analyses.

Representative examples of virtual investigations demonstrate the practical use and the benefits in relation to the vehicle-development process and the networking with concurrent CAE-techniques and Digital Mock-Up.
Introduction

Due to global competition, the automotive industry has to face the challenge of developing new vehicles in very short time frames for a growing variety of new models, increasing customer demands on comfort, performance and quality as well as costs in line with market requirements. During the last ten years, the development cycles at Audi have been reduced from about five to six years to the current three to four years.

Through traditional methods, the required increase in efficiency in vehicle development can only be achieved up to a certain limit. Another essential step to shorten time-to-market is the reorganization of the product-development process and the integration of computer-aided (CA) technologies and methods.

Among the established simulation and numerical analysis methods in vehicle engineering - such as geometry-based methods, crash simulation, strength and fatigue analysis, noise and vibration analyses – multibody simulation using the specialized ADAMS/Car simulation software plays a key role with increasing importance in the vehicle-development process at Audi, particularly in chassis development.
Product-Development Process at Audi

Elastokinematic Suspension Design
Vehicle Dynamics Simulation Method

Integration of Engine Movements in Digital Mock-Up

Prediction Quality of Vehicle Dynamics Simulation
Conclusion

The major fields of application of multibody simulation in virtual vehicle development have been discussed with emphasis on the practical use and the benefits in relation to concurrent CAE-techniques and Digital Mock-Up. Functional virtual checks and assessment of vehicle dynamics behavior based on simulation results play a key role.

The essential strategic role of ADAMS simulation software is obvious. The integrated use of multibody simulation in the product-development process contributes significantly to increase required efficiency in vehicle development.
Fuzzy control for active suspensions

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Abstract

A methodology for the design of active car suspension systems is presented. The goal is to minimize vertical car body acceleration, for passenger comfort, and to avoid hitting suspension limits, for component lifetime preservation. A controller consisting of two control loops is proposed to attain this goal. The inner loop controls a nonlinear hydraulic actuator to achieve tracking of a desired actuation force. The outer loop implements a fuzzy logic controller which interpolates linear locally optimal controllers to provide the desired actuation force. Final controller parameters are computed via genetic algorithm-based optimization. A numerical example illustrates the design methodology. © 2000 Elsevier Science Ltd. All rights reserved.
Adaptive Observers for Active Automotive Suspensions: Theory and Experiment

Rajesh Rajamani, Member, IEEE, and J. Karl Hedrick

Abstract—An adaptive observer is developed for a class of nonlinear systems. Conditions for convergence of state and parameter estimates are presented. The developed theory is used for observer-based parameter identification in the active suspension system of an automobile. A realistic model of the suspension system incorporating the dynamics of the hydraulic actuator is used. The observer is used to adapt on dry friction which is usually present in significant magnitudes in hydraulic actuators. The observer can also be used to adapt on spring stiffnesses, viscous damping and hydraulic bulk modulus. A special adaptive observer is proposed for identification of the sprung mass of the automobile. Since the sprung mass depends on the number of passengers and the load on the automobile, it needs to be regularly updated.

The adaptive observers use measurements from two accelerometers and an LVDT. They yield good experimental performance when implemented on a half-car suspension test rig.
Control logic for an electric power steering system using assist motor

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Abstract

Electric power steering (EPS) systems have many advantages over traditional hydraulic power steering systems in engine efficiency, space efficiency, and environmental compatibility. This research aims at developing EPS control logic for reduction of steering torque exerted by a driver, realization of various steering feels, and improvement of return-to-center performance. In addition, the torque sensor capable of measuring the steering torque and steering wheel angle is devised, and the hardware-in-the-loop simulation (HILS) system that can implement an actual load torque delivered to the steering column is also developed. With the proposed EPS logic, the driver can turn the steering wheel with the steering torque whose magnitude is determined from a torque map independent of load torques that tend to vary depending on the driving conditions. Experimental studies show that the proposed EPS control logic can improve return-to-center performance of the steering wheel by control of the assist motor. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Electric power steering; Steering torque; Torque sensor; Assist motor; Active damping
ADVANTAGES OF ACTIVE STEERING FOR VEHICLE DYNAMICS CONTROL

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99ME013

Keywords: active steering, robust control, yaw and roll disturbance attenuation, rollover avoidance

Abstract

Yaw and roll dynamics of vehicles can be controlled efficiently by individual wheel braking or by active steering. Both approaches are compared on the basis of physical and application considerations. Two vehicle dynamics control concepts based on active steering are summarized. One of them focuses on the attenuation of yaw disturbances on the vehicle by robust unilateral decoupling of yaw and lateral mode. The other approach aims at rollover avoidance of road vehicles. There, in continuous operation, active steering improves the roll dynamics. In case of emergency an efficient strategy applies simultaneous steering and braking control.
Mechatronic semi-active and active vehicle suspensions

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Abstract

After discussing various principles of suspensions with variable dampers and springs as well as active components, mathematical models of these systems are derived. It is shown how the unknown parameters can be obtained experimentally through parameter estimation by using body accelerometers, wheel accelerometers, and suspension deflection sensors in different combinations. Experimental results are described for suspensions on a test rig and in cars driving over road surfaces. Through recursive parameter estimation these parameters can be obtained on-line in real time. Then, feedback principles are derived for controlling the damping ratio of dampers with proportional magnetic valve actuators. The mathematical models are then used for fault detection and diagnosis of the damper by combining parameter estimation and parity equation methods.

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Keywords: Mechatronic; Semi-active suspension; Control; Parameter estimation; Fault detection
Concurrent Research and Development of a Magnetic Ride Control System

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Abstract—General Motors became the first auto-manufacturer in applying magneto-rheological (MR) fluids to eliminate mechanical valves used in production controllable dampers, and achieve high performance ride and handling on its vehicles beginning with the 2002 Cadillac Seville. The successful introduction of this smart material technology into the highly demanding and cost sensitive arena of the automotive industry was made possible through a highly coordinated multidisciplinary R&D effort at General Motors. This paper focuses only on the R&D stage of this technology development such as the MR materials selection and characterization, MR fluid-based actuator configurations for real-time suspension damping control, modeling and design optimization of the actuators and their performance prediction. Experimental results are provided to verify the predicted damping forces of the actuators based on fluid-flow models. The improvements in vehicle performance based on integrated control of the semi-active magnetic suspension actuators are also demonstrated though vehicle ride metrics test data.

Index Terms—Smart Materials, Controllable Damper, Magneto-rheological (MR) Fluid, Semi-active Suspension.
Permanent-Magnets Linear Actuators Applicability in Automobile Active Suspensions

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Abstract—Significant improvements in automobile suspension performance are achieved by active systems. However, current active suspension systems are too expensive and complex. Developments occurring in power electronics, permanent magnet materials, and microelectronic systems justifies analysis of the possibility of implementing electromagnetic actuators in order to improve the performance of automobile suspension systems without excessively increasing complexity and cost. In this paper, the layouts of hydraulic and electromagnetic active suspensions are compared. The actuator requirements are calculated, and some experimental results proving that electromagnetic suspension could become a reality in the future are shown.

Index Terms—Active suspension, automobile suspension, linear actuator, permanent magnet.
Suspension Systems

- When people think of automobile performance, they normally think of horsepower, torque, and 0-60 acceleration. But all of the power generated by a piston engine is useless if the driver can't control the car. That's why automobile engineers turned their attention to the suspension system almost as soon as they had mastered the four-stroke internal combustion engine.
• **The job of a car suspension is:**
  – to maximize the friction between the tires and the road surface
  – to provide steering stability with good handling
  – to ensure the comfort of the passengers
• If a road were perfectly flat, with no irregularities, suspensions wouldn't be necessary. But roads are far from flat. Even freshly-paved highways have subtle imperfections that can interact with the wheels of a car. It's these imperfections that apply forces to the wheels that result in wheel acceleration.
• Without an intervening structure, all of wheel's vertical energy is transferred to the frame, which moves in the same direction. In such a situation, the wheels can lose contact with the road completely. Then, under the downward force of gravity, the wheels can slam back into the road surface.

• What you need is a system that will absorb the energy of the vertically-accelerated wheel, allowing the frame and body to ride undisturbed while the wheels follow bumps in the road.
The study of the forces at work on a moving car is called **vehicle dynamics**. Most automobile engineers consider the dynamics of a moving car from two perspectives:

- **Ride** - a car's ability to smooth out a bumpy road
- **Handling** - a car's ability to safely accelerate, brake, and corner

These two characteristics can be further described in three important principles:

- road isolation
- road holding
- cornering
The tables below describe these principles and how engineers attempt to solve the challenges unique to each.

<table>
<thead>
<tr>
<th>Principle</th>
<th>Definition</th>
<th>Goal</th>
<th>Solution</th>
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</thead>
<tbody>
<tr>
<td>Road Isolation</td>
<td>The vehicle's ability to absorb or isolate road shock from the passenger compartment</td>
<td>Allow the vehicle body to ride undisturbed while traveling over rough roads</td>
<td>Absorb energy from road bumps and dissipate it without causing undue oscillation in the vehicle</td>
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<td>Road Holding</td>
<td>The degree to which a car maintains contact with the road surface in various types of directional changes and in a straight line. Example: The weight of a car will shift from the rear tires to the front tires during braking. Because the nose of the car dips toward the road, this type of motion is known as &quot;dive.&quot; The opposite effect -- &quot;squat&quot; -- occurs during acceleration, which shifts the weight of the car from the front tires to the back.</td>
<td>Keep the tires in contact with the ground, because it is the friction between the tires and the road that affects a vehicle's ability to steer, brake, and accelerate.</td>
<td>Minimize the transfer of vehicle weight from side to side and front to back, as this transfer of weight reduces the tire's grip on the road.</td>
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<tr>
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<tr>
<td>Cornering</td>
<td>The ability of a vehicle to travel a curved path</td>
<td>Minimize body roll, which occurs as centrifugal force pushes outward on a car's center of gravity while cornering, raising one side of the vehicle and lowering the opposite side</td>
<td>Transfer the weight of the car during cornering from the high side of the vehicle to the low side</td>
</tr>
</tbody>
</table>
• **Car Suspension Parts**
  - A *car's suspension*, with its various components, provides all of the solutions described.
  - The suspension of a car is actually *part of the chassis*, which comprises all of the important systems located beneath the car's body.
– **Frame** - structural, load-carrying component that supports the car's engine and body, which are in turn supported by the suspension

– **Suspension System** - setup that supports weight, absorbs and dampens shock, and helps maintain tire contact

– **Steering System** - mechanism that enables the driver to guide and direct the vehicle

– **Tires and Wheels** - components that make vehicle motion possible by way of grip and/or friction with the road

• So the suspension is just one of the major systems in any vehicle.
- **Springs**
  - Today's springing systems are based on one of four basic designs.
- **Coil springs** - This is the most common type of spring and is, in essence, a heavy-duty torsion bar coiled around an axis. Coil springs compress and expand to absorb the motion of the wheels.
• **Leaf Springs** - This type of spring consists of several layers of metal (called "leaves") bound together to act as a single unit. Leaf springs were first used on horse-drawn carriages and were found on most American automobiles until 1985. They are still used today on most trucks and heavy-duty vehicles.
• **Torsion Bars** - Torsion bars use the twisting properties of a steel bar to provide coil-spring-like performance. One end of a bar is anchored to the vehicle frame. The other end is attached to a wishbone, which acts like a lever that moves perpendicular to the torsion bar. When the wheel hits a bump, vertical motion is transferred to the wishbone and then, through the levering action, to the torsion bar. The torsion bar then twists along its axis to provide the spring force.
• **Air Springs** - Air springs, which consist of a cylindrical chamber of air positioned between the wheel and the car's body, use the compressive qualities of air to absorb wheel vibrations. The concept is actually more than a century old and could be found on horse-drawn buggies. Air springs from this era were made from air-filled, leather diaphragms, much like a bellows; they were replaced with molded-rubber air springs in the 1930s.
• **Springs: Sprung and Un-sprung Mass**
  – The sprung mass is the mass of the vehicle supported on the springs, while the un-sprung mass is loosely defined as the mass between the road and the suspension springs. The stiffness of the springs affects how the sprung mass responds while the car is being driven.
  – **Loosely-sprung cars**, such as luxury cars, can swallow bumps and provide a super-smooth ride; however, such a car is prone to dive and squat during braking and acceleration and tends to experience body sway or roll during cornering.
  – **Tightly- sprung cars**, such as sports cars, are less forgiving on bumpy roads, but they minimize body motion well, which means they can be driven aggressively, even around corners.
– So, while springs by themselves seem like simple devices, designing and implementing them on a car to balance passenger comfort with handling is a complex task.

– And to make matters more complex, springs alone can't provide a perfectly smooth ride. Why? Because springs are great at absorbing energy, but not so good at dissipating it. Other structures, known as dampers, are required to do this.
**Dampers: Shock Absorbers**

- Unless a dampening structure is present, a car spring will extend and release the energy it absorbs from a bump at an uncontrolled rate. The spring will continue to bounce at its natural frequency until all of the energy originally put into it is used up. A suspension built on springs alone would make for an extremely bouncy ride and, depending on the terrain, an uncontrollable car.

- Enter the shock absorber, or snubber, a device that controls unwanted spring motion through a process known as dampening. Shock absorbers slow down and reduce the magnitude of vibratory motions by turning the kinetic energy of suspension movement into heat energy that can be dissipated through hydraulic fluid.
A shock absorber is basically an oil pump placed between the frame of the car and the wheels. The upper mount of the shock connects to the frame (i.e., the sprung weight), while the lower mount connects to the axle, near the wheel (i.e., the un-sprung weight). In a twin-tube design, one of the most common types of shock absorbers, the upper mount is connected to a piston rod, which in turn is connected to a piston, which in turn sits in a tube filled with hydraulic fluid. The inner tube is known as the pressure tube, and the outer tube is known as the reserve tube. The reserve tube stores excess hydraulic fluid.
– When the car wheel encounters a bump in the road and causes the spring to coil and uncoil, the energy of the spring is transferred to the shock absorber through the upper mount, down through the piston rod and into the piston. Orifices perforate the piston and allow fluid to leak through as the piston moves up and down in the pressure tube. Because the orifices are relatively tiny, only a small amount of fluid, under great pressure, passes through. This slows down the piston, which in turn slows down the spring.

– Shock absorbers work in two cycles -- the compression cycle and the extension cycle.

  • The compression cycle occurs as the piston moves downward, compressing the hydraulic fluid in the chamber below the piston.
• The extension cycle occurs as the piston moves toward the top of the pressure tube, compressing the fluid in the chamber above the piston. A typical car or light truck will have more resistance during its extension cycle than its compression cycle. With that in mind, the compression cycle controls the motion of the vehicle's un-sprung weight, while extension controls the heavier, sprung weight.

  All modern shock absorbers are velocity-sensitive -- the faster the suspension moves, the more resistance the shock absorber provides. This enables shocks to adjust to road conditions and to control all of the unwanted motions that can occur in a moving vehicle, including bounce, sway, brake dive, and acceleration squat.
• **Dampers: Struts and Anti-sway Bars**

Another common dampening structure is the strut -- basically a shock absorber mounted inside a coil spring. **Struts perform two jobs:** They provide a dampening function like shock absorbers, and they provide structural support for the vehicle suspension. That means struts deliver a bit more than shock absorbers, which don't support vehicle weight -- they only control the speed at which weight is transferred in a car, not the weight itself.
Because shocks and struts have so much to do with the handling of a car, they can be considered critical safety features. Worn shocks and struts can allow excessive vehicle-weight transfer from side to side and front to back. This reduces the tire's ability to grip the road, as well as handling and braking performance.

- **Anti-Sway Bars**
– Anti-sway bars (also known as anti-roll bars) are used along with shock absorbers or struts to give a moving automobile additional stability. An anti-sway bar is a metal rod that spans the entire axle and effectively joins each side of the suspension together.

– When the suspension at one wheel moves up and down, the anti-sway bar transfers movement to the other wheel. This creates a more level ride and reduces vehicle sway. In particular, it combats the roll of a car on its suspension as it corners. For this reason, almost all cars today are fitted with anti-sway bars as standard equipment, although if they're not, kits make it easy to install the bars at any time.
• **Suspension Types: Front**
  – The four wheels of a car work together in **two** independent systems -- the two wheels connected by the front axle and the two wheels connected by the rear axle. That means that a car can and usually does have a different type of suspension on the front and back. Much is determined by whether a rigid axle binds the wheels or if the wheels are permitted to move independently.
  – The former arrangement is known as a **dependent system**, while the latter arrangement is known as an independent system.
– Dependent Front Suspensions

• Dependent front suspensions have a rigid front axle that connects the front wheels. Basically, this looks like a solid bar under the front of the car, kept in place by leaf springs and shock absorbers. Common on trucks, dependent front suspensions haven't been used in mainstream cars for years.

– Independent Front Suspensions

• In this setup, the front wheels are allowed to move independently. The MacPherson strut, developed by Earle S. MacPherson of General Motors in 1947, is the most widely used front-suspension system.

• The MacPherson strut combines a shock absorber and a coil spring into a single unit. This provides a more compact and lighter suspension system that can be used for front-wheel drive vehicles.
The double-wishbone suspension, also known as an A-arm suspension, is another common type of front independent suspension.

While there are several different possible configurations, this design typically uses two wishbone-shaped arms to locate the wheel. Each wishbone, which has two mounting positions to the frame and one at the wheel, bears a shock absorber and a coil spring to absorb vibrations.

Double-wishbone suspensions allow for more control over the camber angle of the wheel, which describes the degree to which the wheels tilt in and out. They also help minimize roll or sway and provide for a more consistent steering feel. Because of these characteristics, the double-wishbone suspension is common on the front wheels of larger cars.
• **Suspension Types: Rear**
  
  – Dependent Rear Suspensions

  • **Leaf spring** – If a solid axle connects the rear wheels of a car, then the suspension is usually quite simple -- based either on a leaf spring or a coil spring.

  • In the former design, the leaf springs clamp directly to the drive axle. The ends of the leaf springs attach directly to the frame, and the shock absorber is attached at the clamp that holds the spring to the axle. For many years, American car manufacturers preferred this design because of its simplicity.
• The same basic design can be achieved with coil springs replacing the leaves. In this case, the spring and shock absorber can be mounted as a single unit or as separate components. When they're separate, the springs can be much smaller, which reduces the amount of space the suspension takes up.

– Independent Rear Suspensions

• If both the front and back suspensions are independent, then all of the wheels are mounted and sprung individually, resulting in what car advertisements tout as "four-wheel independent suspension."
• Any suspension that can be used on the front of the car can be used on the rear, and versions of the front independent systems previously described can be found on the rear axles.

• Of course, in the rear of the car, the steering rack - the assembly that includes the pinion gear wheel and enables the wheels to turn from side to side -- is absent. This means that rear independent suspensions can be simplified versions of front ones, although the basic principles remain the same.
• Specialized Suspensions: Formula One Racers
  – The Formula One racing car represents the pinnacle of automobile innovation and evolution. Lightweight, composite bodies, powerful V10 engines, and advanced aerodynamics have led to faster, safer, and more reliable cars.
To elevate driver skill as the key differentiating factor in a race, stringent rules and requirements govern Formula One racecar design. For example, the rules regulating suspension design say that all Formula One racers must be conventionally sprung, but they don't allow computer-controlled, active suspensions. To accommodate this, the cars feature multi-link suspensions, which use a multi-rod mechanism equivalent to a double-wishbone system.

Recall that a double-wishbone design uses two wishbone-shaped control arms to guide each wheel's up-and-down motion. Each arm has three mounting positions -- two at the frame and one at the wheel hub -- and each joint is hinged to guide the wheel's motion.
In all cars, the primary benefit of a double-wishbone suspension is control. The geometry of the arms and the elasticity of the joints give engineers ultimate control over the angle of the wheel and other vehicle dynamics, such as lift, squat, and dive.

Unlike road cars, however, the shock absorbers and coil springs of a Formula One racecar don't mount directly to the control arms. Instead, they are oriented along the length of the car and are controlled remotely through a series of pushrods and bell cranks. In such an arrangement, the pushrods and bell cranks translate the up-and-down motions of the wheel to the back-and-forth movement of the spring-and-damper apparatus.
• **The Bose Suspension System**
  
  – While there have been enhancements and improvements to both springs and shock absorbers, the basic design of car suspensions has not undergone a significant evolution over the years.
  
  – But all of that’s about to change with the introduction of a brand-new suspension design conceived by Bose -- the same Bose known for its innovations in acoustic technologies. Some experts are going so far as to say that the Bose suspension is the biggest advance in automobile suspensions since the introduction of an all-independent design.
The Bose system uses a linear electromagnetic motor (LEM) at each wheel in lieu of a conventional shock-and-spring setup. Amplifiers provide electricity to the motors in such a way that their power is regenerated with each compression of the system. The main benefit of the motors is that they are not limited by the inertia inherent in conventional fluid-based dampers. As a result, an LEM can extend and compress at a much greater speed, virtually eliminating all vibrations in the passenger cabin. The wheel's motion can be so finely controlled that the body of the car remains level regardless of what's happening at the wheel. The LEM can also counteract the body motion of the car while accelerating, braking, and cornering, giving the driver a greater sense of control.