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Design and Experimental Investigation of Demand Dependent Active Suspension for Vehicle Rollover Control

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Abstract

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Design and Experimental Investigation of Demand Dependent Active Suspension for Vehicle Rollover Control

Lifu Wang, Nong Zhang and Haiping Du

Abstract—**This paper presents a novel design for Demand Dependent Active Suspension (DDAS) focusing on vehicle rollover control. Active suspensions take credit for improving ride comfort and handling performance, but to use active suspension in vehicle rollover control has not been widely investigated. The proposed active suspension design consists of four double direction hydraulic actuators, hydraulically interconnected, and it can actively tilt the vehicle against its roll motion by supplying a required restoring moment, which is over the competence of passive or semi-active suspension. Based on a real vehicle fitted with DDAS, the experimental investigation validates the effectiveness of DDAS in vehicle rollover control.**

I. INTRODUCTION

SUSPENSION which connects a vehicle body to its wheels is a very important system for reducing vibration effects over rough ground. Suspensions can be classified into three categories: passive, semi-active, and active suspension. Passive suspensions achieve the road-induced vibration isolation through passive means such as springs and dampers or shock absorbers [1].

The semi-active suspension modulates the damping force by adjusting the orifice area in the damper, thus changing the resistance of fluid flow, in accordance with operating conditions [2-3]. However, it cannot input external energy into system which makes the most distinct difference from active suspensions.

A requirement to characterize active suspensions is that at least a portion of suspension force is generated from active power sources [1]. Active suspensions require sensors to be located at different points of the vehicle to measure the motions of the body and suspension [2], and its parameters can be adjusted by a controller.

Active suspensions use electronic monitoring of vehicle conditions, coupled with the means to impact vehicle suspension and behavior in real time to directly control the motion of the car. Electrical, pneumatic and hydraulic actuators are commonly used as force generators. To generate external force, actuators may consume large amounts of energy [2-3]. Therefore, the energy consumption should be considered as an important factor in the active suspension design.

Suspensions also can be classified into independent and dependent suspensions. Independent suspensions allow each wheel to move individually without affecting other wheels. Dependent suspensions means one wheel's movement affects the others, usually realized by interconnecting the hydraulic or pneumatic actuators in some way [4].

Active suspensions offer substantial benefits in ride comfort and handling control over traditional system. Hence, in the past three decades, using active suspensions to improve ride comfort has attracted considerable attention [1-2, 5-8]. However, the possibility of applying active suspension technology to improve vehicle on-road safety, specifically in rollover control, has not been extensively studied.

A rollover crash is more dangerous than non-rollover crashes. According to the National Highway Traffic Safety Administration (NHTSA) of USA, in 2000, rollover accidents killed 9,873 people, almost one-third of the total deaths of occupants of passenger cars and light trucks [9]. The suspension is believed to have unique abilities among other vehicle subsystems to affect vehicle roll motion, for example, by increasing vehicle roll stiffness in conventional passive or semi-active suspension. Unlike these suspensions, active suspension can further effectively reduce the tendency of vehicle rollover by directly supplying an anti-roll moment to the vehicle body.

Active suspensions can remarkably govern the roll motion of a vehicle body. The suspension stoke of a light vehicle is around 0.25m, which can tilt the vehicle body in the roll plane by a maximum of around 10 degrees [10]. Paper [10] also shows simulation results of applying active suspension for roll control. However, the practical design and experimental investigation of this application has not been widely studied yet.

This paper presents the design of a Demand Dependent Active Suspension (DDAS), a system which has the potential ability to control vehicle vibration in multi-mode in the future. However, as the first step of DDAS design, this paper illustrates the design concept and focuses on only one aspect of its multifunction, which is roll control. Two rollover propensity tests proved the effectiveness of DDAS, which can actively tilt the vehicle against its roll by supplying restoring forces, from four interconnected hydraulic actuators. Hydraulic power is drawn from a mechanical power steering pump, and the hydraulic circuits are controlled by an

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innovative valve network. For roll control, signals such as speed and steering angle [10], lateral acceleration, and roll angle are commonly considered as indicators. In this design, roll angle over a certain level triggers the system.

II. MODELING

A. *Modeling of active suspension*

Dynamic modeling of vehicle active suspensions has been widely studied [1, 6-7, 11]. Fig. 1 shows a 9-DOF full-car model with suspension presented in [10].

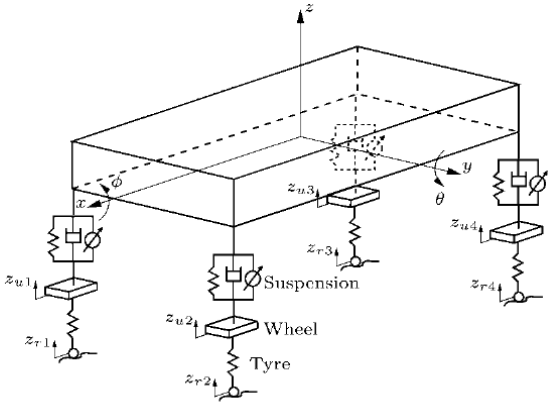

Fig. 1. Vehicle dynamic model [10]. This full-car model includes active suspension. There are four force generators in each corner of the chassis.

Fig. 1, shows the vehicle model, where

Φ roll angle of vehicle body

θ pitch angle of vehicle body

z_{si} the ***i***th wheel vertical displacement

z_{ri} vertical road displacement on the ***i***th wheel

As shown in Fig. 1, each quarter of the active suspension consists of a spring, a damping valve and a force generator connected in parallel. It can be used to analyze complex vehicle motions. DDAS has the potential ability to control multi-mode vehicle vibration, i.e., bounce, roll, pitch and articulation, by switching the hydraulic circuit to different settings. To achieve the full functional control of DDAS, it has to take several steps, and this study starts from the vehicle roll control, where a simplified 4-DOF half-car model can be used.

B. *Simplified vehicle rolling model and controller design*

Vehicle rolling dynamics can be very complex. Some mathematical models are derived for advanced control, e.g., model in [12]. However, a simple model will help give a clear idea for understanding this novel complicated rollover control system. The model in Fig. 2 is used to illustrate the vehicle dynamics under extreme steering. Without considering tyre slipping, the vehicle body rolls about its roll center due to the lateral acceleration applied to the body mass center.

The aim of roll control is to maintain the vehicle in a horizontal position. Fig. 2 shows that the vehicle body rolling moment is counteracted by a restoring moment generated by a pair of actuators installed on each side of the vehicle. A simple proportional control strategy is adopted here to demonstrate the control concept; further sophisticated controllers can be developed after the validation investigation carried out in this study and the exploration of DDAS dynamic character in the future study.

The proportional feedback control can be seen in the block diagram, Fig. 3, where the actuating force is proportional to the roll angle.

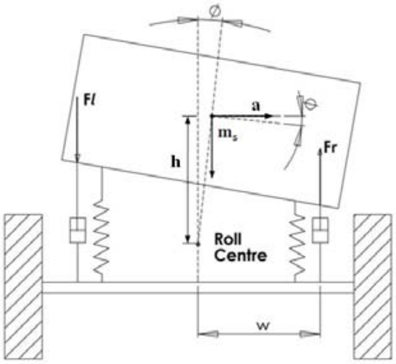

Fig. 2. Vehicle rolling diagram.

Where: m_s is the sprung mass; h is distance between sprung mass center and roll centre; w is the distance between suspension and the centre of the vehicle; a is the lateral acceleration; F_l, F_r are the restoring forces supplied by the actuators.

Hence the roll moment caused by the lateral acceleration is

$$M_r = m_s a h + m_s g h \Phi \tag{1}$$

Restoring moment from the actuators is

$$M_f = -F_l w - F_r w \tag{2}$$

The whole moment equation of sprung mass is

$$\sum M = M_r + M_f = m_s a h + m_s g h \Phi - F_l w - F_r w \tag{3}$$

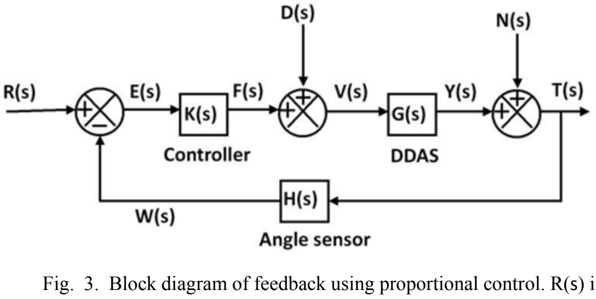

Fig. 3. Block diagram of feedback using proportional control. R(s) is the reference input, in this case is zero, D(s) is the disturbance input, N(s) is the noise input, E(s) is the control error, F(s) is the control input, and Y(s) is the system output [13].

DDAS system delay (e.g., valve switching time, actuator delay) is not considered in the proportional controller, but investigated during the experiment and discussed in this paper. In Fig. 3, the transfer function from the disturbance input to the measured output is detailed in (4).

$$\frac{Y(s)}{D(s)} = \frac{G(s)}{1+K(s)G(s)H(s)}$$

$$F(s) = K(s)E(s)$$

$K(s)$ is the controller of which parameters will be obtained from experiment.

$E(s)$ is roll angle error signal

$F_{(s)}$ is the restoring force

A high proportional gain results in a large restoring moment for a given change in angle error. It commonly gives a quick response, but increased overshoot into system. In this paper, the gain is tuned from the experiment.

III. DESIGN OF DDAS

This active suspension design consists of four double direction hydraulic actuators, hydraulically interconnected, powered by a mechanical steering pump and controlled by a compact manifold. DDAS can actively tilt the vehicle against its motions, e.g. rollover, by supplying required restoring forces, which is beyond the capabilities of passive or semi-active suspension systems. The DDAS function is shown in Fig. 4.

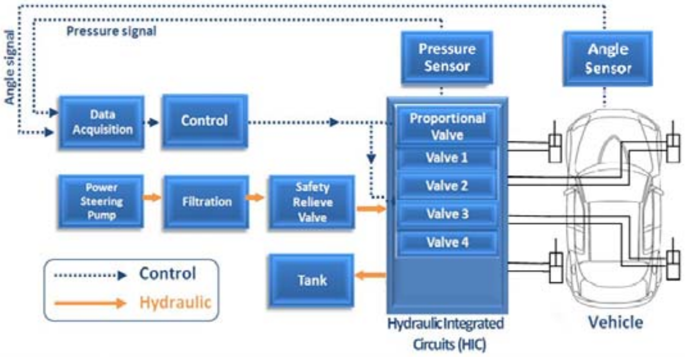

Fig. 4. DDAS functional flowchart.

The compressed oil from the mechanical power steering pump is regulated by a proportional valve in the manifold, and the hydraulic circuits can be reconfigured in real time by switching a group of solenoid valves. Using angle signal, which is collected from an angle sensor installed in the vehicle, the controller controls the proportional pressure relieve valve to change the pressure and directs the solenoid valves to deal with the vibration modes by setting up the required hydraulic circuits.

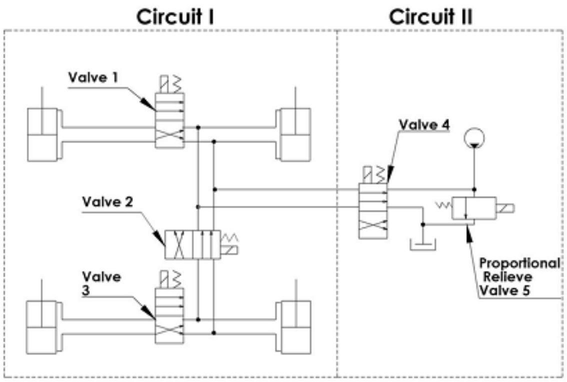

Fig. 5. DDAS hydraulic layout. In prototype, valves are integrated into the HIC manifold, however, in the future design, they can be separately arranged.

HIC can be divided into two fluid circuits: Circuit I, a mode-select circuit and Circuit II, a force-control circuit, as shown in Fig. 5. Circuit I consists of four double direction hydraulic actuators, valve 1, 2, 3, and the conduits between them. Circuit II comprises valve 4 and proportional relieve valve 5.

Circuit I can target a specified vehicle vibration mode, by changing the way that the hydraulic cylinders interconnect. This enables DDAS to supply different restoring forces or moments to control different vehicle motions. For example, to control roll motion, Circuit I can be switched to anti-roll mode, where the top chambers from the left side actuators are connected to the bottom chambers from the right side actuators, and vice verse. Hence, the actuated forces form a restoring moment. The default setting of Circuit I is anti-roll mode, as shown in Fig. 5.

Circuit II, a force-control circuit, regulates the oil pressure to control the magnitude of actuated forces, which is proportional to the roll angle in this prototype. The following parts details the technologies employed in DDAS.

A. Hydraulic Actuators

Electrical and hydraulic actuators are commonly used in active suspension design. Electrical actuators react quickly and accurately, but their exorbitant prices limit the application in economical vehicles, and nevertheless their excessive energy consumption makes the application only available in luxury vehicles. Compared with electrical actuators, hydraulic actuators have two advantages: cost effective and energy efficient, which make the priority of using the hydraulic actuators in our case. Hydraulic systems have two disadvantages, time delay and complicated hydraulic dynamics; however, they can be improved by optimizing hydraulic system design, using sophisticated mechanical-hydraulic dynamic model and applying advanced control strategies.

B. Dependent Suspension Arrangement

Active suspension arrangements can be either independent or dependent. Independent active suspensions control each actuator individually, while the dependent active suspensions are able to control the circuits which are formed by interconnected actuators. Although independent arrangement of actuators enables the system to react in an ideal way, it has many disadvantages such as increased cost, complicated controller designs and high energy consumption.

To reduce the cost, instead of using the ideal independent layout in active suspensions, one attempt is to adopt compact interconnected structure into suspension design. The benefit will be the lower cost, reduced power requirements, less complexity and therefore increased reliability. An industry application is the diagonally hydraulically interconnected active suspension used by Audi in their RS6 racing car.

DDAS is a novel design of hydraulically interconnected active suspension, wherein the vehicle's individual suspension actuators (i.e., hydraulic cylinders) are connected to one another. This, in principle, affords the designer greater freedom to simplify the suspension structure and reduce the consumption of energy.

Combining Circuit I and Circuit Ⅱ enables DDAS to work in different modes to supply appropriate restoring forces or moments. For example, to deal with vehicle rollover, DDAS switches suspension into anti-roll mode and supplies the restoring forces to resist it. To investigate the validation of DDAS, this study experimentally verifies the roll control ability as the first step leading to future design.

C. Demand suspension

Demand function avoids the over sensitive reaction of the suspension, which saves energy and prolongs system longevity. The active suspension has the ability to promptly act to tilt the vehicle; however, active control should avoid ‘nulling’ tilt control because drivers need some feeling of acceleration [10]. And most importantly, the active suspension consumes energy when it acts. Hence, DDAS should be used only to deal with a certain range of vehicle vibration frequency, e.g., a limited low bandwidth, such as vibrations of less than 3 Hz, or a specified vehicle vibration mode, e.g., roll. Demand function results in less energy consumed for fewer tasks assigned to active suspensions. If DDAS concentrates on the main vibration mode at a time, the control will be more focus and efficient; the system will still have comparable effectiveness with much lower energy consumption, and this is especially meaningful for industry application. In this prototype test, for roll control, DDAS only turns to be active when the vehicle roll angle reaches a certain level.

IV. EXPERIMENTAL INVESTIGATION

To verity the ability of DDAS in anti-roll control, the following experimental investigation is presented. The test rig consists of two parts: a vehicle fitted with a DDAS and a roll motion stimulator, which is a pair of pneumatic cylinders installed at both sides of the vehicle. A National Instruments Signal Conditioner and Labview are used to process data and control. Proportional control is employed as the control strategy.

A. Configuration

Vehicle used as the test bed is a 1988 model Mitsubishi Magna sedan, shown in Fig. 6. Its tare weight is 1190Kg and it presents a fairly standard family vehicle. A vehicle power steering pump is used as the hydraulic oil supplier. The pump speed is 1400rpm, and the measured flow rate is 9L/min.

Fig. 6. Test bed.

The simulated vehicle roll moment used as disturbance is generated by two pneumatic cylinders, and one is shown in Fig. 7. They can roll the vehicle with various frequencies, adjusted by a controller, to simulate the vehicle roll motion during steering. The cylinder extending and contracting force are 1951N and 1612N respectively.

Fig. 7. Pneumatic cylinder as roll generator.

The configuration of the prototype of DDAS is shown in Fig. 8. Four double direction hydraulic actuators are installed into the vehicle, with the control valves and other hydraulic components, including a filter and a safety relief valve.

Manifold shown in Fig. 9, manufactured by Hydraulic Controls Pty Ltd, has the function discribed in Fig. 5. A proportional pressure relief valve selected from Wandfluh Hydraulic Company with a type code BVPPM22-100-G24, is installed in the bottom of this manifold. It is driven by an accompanied proportional amplifier and used to regulate the oil pressure. All the valves are controlled by the data processing system shown in Fig. 10.

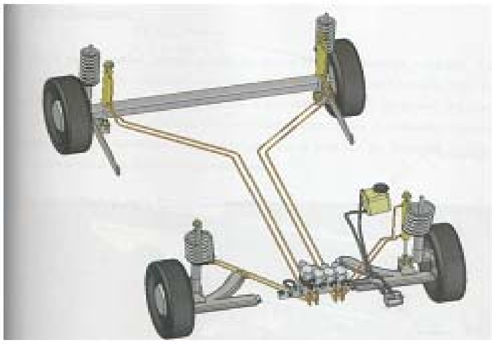

Fig. 8. DDAS hydraulic arrangement. All the valves are integrated in a manifold.

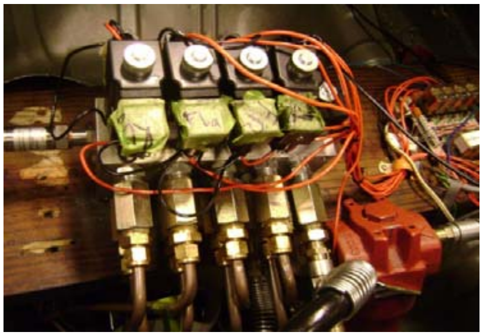

Fig. 9. Hydraulic Integrated Circuits (HIC) manifold.

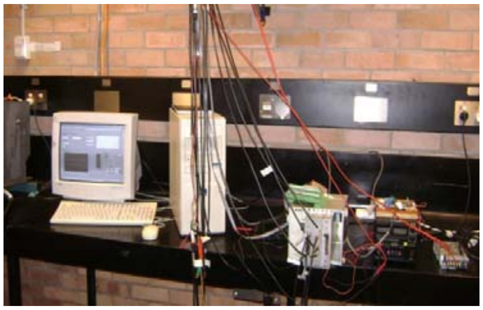

Fig. 10. Data processing system.

As shown in Fig. 10, the data processing system consists of a computer with Labview software, a National Instrument Signal Conditioner and an I/O card. A Ratiometric Vertical Clinometer is used as the angle sensor. Angle signal is gathered from the sensor array by the National Instrument Signal Conditioner and processed by the Labview, with the proportional controller, the front panel of which is shown in Fig. 11. Control signals output from the I/O card are accessed by using the National Instruments Signal Conditioner. The proportional valve control signal is from an analogue output channel and other valves control signals are from digital output channels.

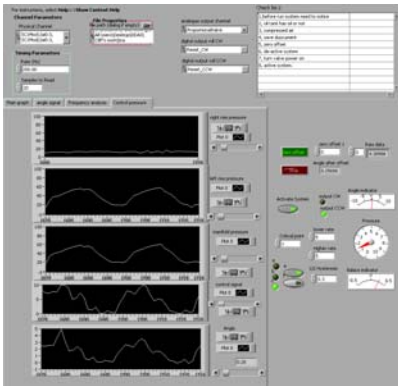

Fig. 11. The front panel of proportional controller

B. Test and result

Two of untripped rollover propensity maneuvers are chosen to test the vehice fitted with DDAS, which are the J-turn maneuver and Fishhook maneuver [14]. The pneumatic cylinders roll the vehicle to simulate the rolling effects of vehicle's J-turn and Fishhook maneuvers on road, and the performance of DDAS is examed in both cases.

1) J-Turn Mneuver test

This maneuver tests the vehicle rollover propensity by suddenly making a large turn, when the vehicle is initially driven in a straight line. The vehicle will roll to one side due to the severe turn [14].

Fig. 12 shows the effect of DDAS in vehicle J-turn test. The dashed line represents the roll angle of vehicle body in J-turn. In this J-turn maneuver, the vehicle starts rolling to one side at time 1.0 second. The roll anlge rises up to the maximum near 3 degrees at 2.5 second, then drops back to 0 degree at round 5 second. In contrast, the solid line shows that DDAS reduces the maximum vehicle roll angle to approximate 1.5 degrees, around 45% decrease, which is significant and very meaningful for preventing vehicle rollover accident.

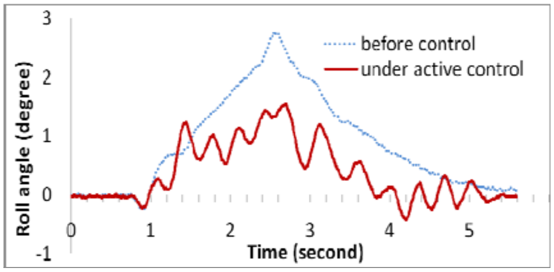

Fig. 12. Roll angel of vehicle in time domain.

2) Fishhook Maneuver

The Fishhook maneuver makes a large turn and then turns back in the opposite direction, which might happen when a driver performs a double lane change [14]. To simulate this maneuver, the pneumatic cylinders tilt the vehicle to one direction, then switch to another direction. In Fig. 13, dotted line represents the vehicle roll under Fishhook maneuver, while the roll angle is up to 4 degrees in both directions. The solid line represents the DDAS's performance, the maximum roll angle reduced to around 3 degrees in both directions, a 25% reduction. The results from the fishhook maneuver test show that DDAS increases the vehicle anti-roll ability and it can reduce the propensity of vehicle rollover.

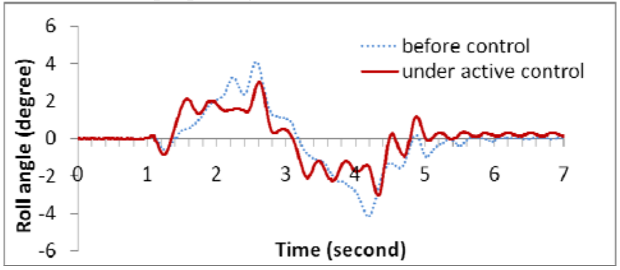

Fig. 13. Roll angel of vehicle under continue roll.

C. Remarks

1) Proportional control: a simple control strategy used in experimental investigation helps to clearly illustrate this roll control system ability and characters. DDAS has some unknown parameters, such as hydraulic delay and mechanical-hydraulic dynamics, which haven't been fully studied yet. Because of this, advanced controllers may not be suitable in this early phase of investigation, which focuses more on control concept development and function validation.

2) System delay: delay includes computing time, valve reacting time and hydraulic response delay. Due to the experimental limitation, the computing time is roughly 20ms, the pressure relieve valve delay is around 15ms and the switching valve reacting time is about 44 ms, found experimentally. Compared with the nature roll frequency of the test rig which is around 3 Hz, the system delay is slightly too much and not able to control the 3Hz vibration smoothly. It results in the unpleased 3Hz oscillation in the graphs.

2) Further investigation: with the results of this investigation, the next phase of the DDAS design will be the hydraulic optimization and the modeling of mechanical-hydraulic dynamics of DDAS. Based on them, some advanced control strategy such as fuzzy control and $H\infty$ control might be applied in active suspension control, e.g., in [5], a delay-dependent memory--less state feedback $H\infty$ controller designed to deal with active vehicle suspension systems with actuator time delay.

V. CONCLUSION

This paper presented a novel multi-mode control concept design of active suspension, by adopting switchable hydraulically interconnected structure, which made the design compact, energy efficient and cost effective. The experimental investigation demonstrated the sound capability of DDAS in counteracting vehicle roll moment.

DDAS significantly reduced vehicle rollover prepotency and increased the vehicle on-road safety. However, it was also noticed that the limitation of the current design in time delay, meant the system was inadequate to deal with the vehicle roll nature frequency which is commonly around 2-3Hz, and this deficiency resulted in the sacrifice of ride comfort. Hence, in this stage, the strategy of DDAS design was focusing more on vehicle safety, e.g. anti-rollover, leaving the ride comfort issue with the passive suspension components such as damper valve.

It will be of interest to practically integrate the vehicle ride into active suspension design in the future, which requires the advanced hydraulic fast reacting system with the time delay within 10ms.

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