

Experimental Investigation of a Hydraulically Interconnected Suspension in Vehicle Dynamics and Stability Control

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ABSTRACT

Mainly motivated by developing cost-effective vehicle anti-roll systems, hydraulically interconnected suspension has been studied in the past decade to replace anti-roll bars. It has been proved theoretically and practically that hydraulic suspensions have superior anti-roll ability over anti-roll bars, and therefore they have achieved commercial success in racing cars and luxury sports utility vehicles (SUVs). However, since vehicle is a highly coupled complex system, it is necessary to investigate/evaluate the hydraulic-suspension-fitted-vehicle's dynamic performance in other aspects, apart from anti-roll ability, such as ride comfort, lateral stability, etc. This paper presents an experimental investigation of a SUV fitted with a hydraulically interconnected suspension under a severe steady steering maneuver; the result is compared with a same type vehicle fitted with anti-roll bars. Furthermore, an insight of how the hydraulic suspension response to extreme maneuvers has been presented, which is of great interest to the optimization of the hydraulic suspension design. Real time simulations are used to assist the experiment to provide a complete picture of the hydraulic system response. The findings are discussed.

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INTRODUCTION

Suspension systems play key roles in road vehicles to ensure an energy-optimal, safe and comfortable driving. Nowadays the dominant suspensions on the market are still passive systems, due to not only their cost effectiveness but also reliabilities. The design of passive independent wheel suspension is a process of compromising, since four wheel vehicles have four suspension modes: bounce, roll, pitch, and warp [1,2,3,4], and they do not share the same preference of stiffness and damping. For example, a soft bounce mode is appreciated by ride comfort, while stiff roll and pitch modes are beneficial for inhibiting vehicle attitude during steering, braking, and acceleration. On the other hand, suspension warp mode should be as soft as possible for road-holding performance.

To overcome these compromises, interconnected suspensions have been adopted as one solution to achieve the vehicle dynamic performance in a particular mode, e.g., increasing stiffness in roll or pitch mode. A good example is anti-roll bars (stabilizer bars), mechanically interconnected suspension systems, employed to increase suspension

stiffness in roll mode. However, since anti-roll bars are not fully uncoupled systems, they bring side effects. For instance, anti-roll bars will undesirably stiffen the suspension warp mode which weaken road holding, especially during off-road drive. One example of the commercial solution to this problem is Toyota's Kinetic Dynamic Suspension System (KDSS), which can effectively disengage anti-roll bars during off-road drive. Another issue with anti-roll bars is that damping can hardly be added in accompanying with the increased torsional stiffness in vehicle roll plane.

Moving from suspension level up to whole vehicle dynamics level, more motions are coupled with those four sprung mass dominated suspension modes to some extends, such as vehicle lateral and yaw motions, which are nursed by/coupled together with suspension warp and roll modes. Firstly, these couplings offer us a great opportunity to indirectly control vehicle lateral/yaw motion by controlling one or a set of according suspension modes. For example, Mercedes Corsswind Assistant demonstrates an indirect control of vehicle yaw through suspension warp mode [5]. The suspension warp mode is generated by pushing diagonal

wheels to the ground through ABC active suspension, which leads to a resulted yaw moments.

Secondly, due to the coupling of vehicle motions and suspension modes, in order to evaluate an anti-roll system, it is necessary to investigate the effects that it brought to other vehicle motions. Hydraulically Interconnected Suspension (HIS) is a low cost, effective anti-roll suspension system. Its anti-roll ability and performance has been studied through analysis and experiment [6]. However, the experimental investigation of HIS in vehicle vertical and lateral motions has not been carried out in field tests yet. This paper presented the experimental study of a vehicle fitted with HIS in roll, vertical and lateral aspects, while using a standard vehicle configured with anti-roll bars as comparison. The paper is organized in the following way. First, a brief background of hydraulically interconnected suspensions is presented, followed by the modeling of a vehicle and a HIS system. Then the field tests are outlined and the obtained experimental results are reported. Simulations are used to further explore the system and guide the experiment.

HYDRAULICALLY INTERCONNECTED SUSPENSIONS

Interconnected suspensions are mainly motivated by the desire of a stiffer vehicle roll mode. A passive interconnected suspension system is one in which the motion (displacement, velocity) at one wheel station can produce forces at other wheel stations, which is generally realized through either mechanical or fluidical means. Interconnected suspensions in a full car level have the theoretically potential ability to uncouple the four suspension modes: roll, bounce, pitching and articulation [1; 4], and have advantages in adjusting stiffness/damping in each of these modes. A comprehensive survey on recent suspension development is presented with a focus on interconnected suspensions [7], and in [8] a survey of passive interconnected suspension has been carried out.

Let's start with mechanically interconnected suspensions. The full-vehicle mechanically interconnected suspensions have been developed and investigated for many years [3], which could decouple the different suspension modes, in order to provide a more favourable compromise between ride and handling requirements. However, their designs are complex and the added weights are considerable. Besides, they are difficult to be tuned to adapt various road and operating conditions.

Unlike mechanical interconnected suspensions which are heavy and difficult to offer additional damping, fluidic suspension systems can offer viable options in improving mode properties. The fluidical interconnection can be realized through hydraulic fluids, pneumatic fluids, or a combination of those two. Full-vehicle fluidically interconnected suspension systems have been investigated on the topics of pneumatically interconnected suspensions [9], hydraulically interconnected suspensions (HIS), [8; 10,11,12,13], hydro-pneumatic suspensions [2; 14,15,16,17], and interconnection

configuration [1; 18]. Variable fluidically interconnected suspensions are developed for different applications.

Cao etc. [2; 14; 15; 19] investigated the dynamics of interconnected hydro-pneumatic suspensions at a full car level, particularly for heavy vehicle applications. The hydro-pneumatic suspension systems have been employed in heavy military vehicles for nearly half a century. The fluidic couplings are realised through hydro-pneumatic struts [17; 20], which have compact design and are claimed to have larger effective working area than normal hydraulic cylinders. The struts provide considerable flexibility for various interconnection configurations among the hydraulic and pneumatic chambers, either hydraulically or pneumatically [19]. A general framework for designing and tuning is included in [2; 14].

Hydraulically interconnected suspensions have achieved commercial success, e.g., Kinetic H2 suspensions, which are originally developed by Australian company Kinetic Pty Ltd. Kinetic H2 suspensions typically contain four double-acting hydraulic cylinders in addition to the original vehicle suspensions. The cylinders are mounted on the car body and the piston rods are fixed on the wheel assemblies. The chambers in the cylinders are interconnected by hydraulic circuits, arranged to counter vehicle roll motion. Each circuit comprises elements such as damper valves, hydraulic accumulators, pipelines, fittings and flexible hoses. Kinetic Dynamic Suspension System (KDSS) is a successful commercial application of this kind of technology, and different versions are available in several applications, e.g., Lexus GX 470 and 200 Series Toyota Land Cruiser. The performance is reported in [13; 21].

Zhang & Smith [8; 10,11,12] recently studied the dynamics of vehicles fitted with HIS systems with a focus on the multi-body system dynamics and interconnected fluid circuit dynamics. A systematic approach are proposed for studying hydraulically interconnected suspensions in both time and frequency domain. The finite element modeling of nonlinear hydraulic system is seamlessly connected to a mass-spring vehicle model through hydraulic-mechanical kinetic coupling, and the theoretical analyses are validated by laboratory experiments [22]. This paper further extended this research to study the transient responses of a typical SUV fitted with a HIS through both simulations and field tests.

MODELING

A brief description of the HIS is provided here in order to give a complete background of the system dynamics. A lumped-mass 9 degrees-of-freedom (DOF) full-car model, as shown in [Figure 1](#), is used in this study. The modeling details of a vehicle fitted with an HIS have been included in [22].

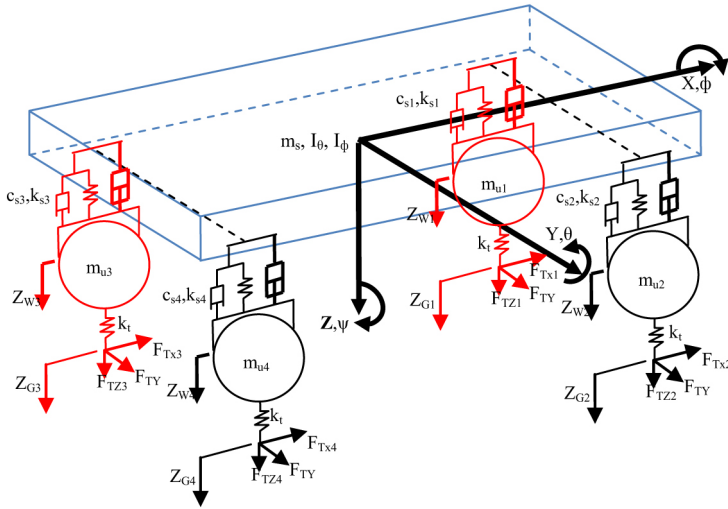


Figure 1. Schematic of a full-car with an HIS

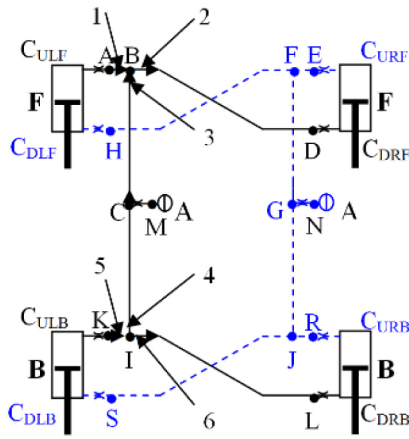


Figure 2. Schematic of a roll-resistant HIS

The vehicle suspension system consists of linear tire damping and springing, linear conventional suspension springing, and a typical HIS system. The car body sprung mass is considered to have five DOF and each of the four wheel unsprung masses has only one DOF in vertical direction. Magic-Formula tire models are used to calculate the contact forces. From Figure 1, it can be seen that the shock absorbers of conventional independent suspensions between the sprung and unsprung masses are kept with the car. The added typical roll-resistant HIS arrangement for this application consists of two identical hydraulic circuits as shown in Figure 2. The two hydraulic circuits are coupled with each other kinetically via four identical double acting piston-cylinder actuators. Each of the hydraulic circuits comprises a nitrogen-filled diaphragm accumulator, and hydraulic pipeline elements. The HIS circuits often include additional elements, such as hydraulic fittings and flexible hoses, but they fall beyond the consideration of this investigation.

Within the two hydraulic circuits, the cylinders are mounted on the car body and the piston rods are fixed on the wheel stations. The dynamic interaction between the hydraulic system and the sprung and unsprung masses can be described as such: relative velocities in the suspension struts cause the changes of pressure in both circuits, which leads to the changes of suspension strut forces through four cylinders. As a result, vehicle body and wheel motions occur, which, in turn, affect the hydraulic system. This mechanic-hydraulic interaction will continue until the system reaches a new equilibrium. HIS systems can provide greater freedom to independently specify modal stiffness and damping characteristics. The working mechanisms and features of the full-car HIS system can be found in [12].

STATE SPACE EQUATIONS

The details of derivation of the state space equations of the combined vehicle multi-body system and hydraulic circuits for transient analysis can be found in [12]. Here a brief description of the dynamic model is provided, including the state space representation of the integrated full-car system for the transient analysis. The state vector describing the motion of the sprung and unsprung lumped multi-body subsystem is defined as

$$X_M = [Z^T \dot{Z}^T]^T \quad (1)$$

where displacement vector is

$$Z = [Y_{V0} \ Z_{V0} \ Z_{W1} \ Z_{W2} \ Z_{W3} \ Z_{W4} \ \phi_{XV} \ \theta_{YV} \ \psi_{ZV}]^T \quad (2)$$

and velocity vector is

$$\dot{Z} = [\dot{Y}_{V0} \ \dot{Z}_{V0} \ \dot{Z}_{W1} \ \dot{Z}_{W2} \ \dot{Z}_{W3} \ \dot{Z}_{W4} \ \dot{\phi}_{XV} \ \dot{\theta}_{YV} \ \dot{\psi}_{ZV}]^T \quad (3)$$

The state vector describing the dynamic states of the hydraulic subsystem is defined as

$$X_H = [P_U^{C1} \ P_A^{AB} \ P_B^{AB} \ Q_B^{AB} \ P_M^{ABM} \ P_C^{BC} \ Q_C^{BC} \ Q_C^{CI} \ P_I^{CI} \ Q_I^{CI} \dots \\ Q_I^{IL} \ P_L^{IL} \ P_B^{C4} \ P_U^{C2} \ P_E^{EF} \ P_F^{EF} \ Q_F^{EF} \ P_N^{AFN} \ P_G^{FG} \ Q_G^{FG} \ Q_G^{GJ} \dots \\ P_J^{GJ} \ Q_J^{GJ} \ Q_J^{JS} \ P_S^{JS} \ P_B^{C3} \ P_D^{CD} \ P_B^{C2} \ P_U^{C3} \ P_K^{KI} \ P_H^{GH} \ P_B^{C1} \dots \\ P_U^{C4} \ P_R^{RJ}]^T \quad (4)$$

Through integrating the two state vectors together, the state vector of the full car with a HIS is obtained

$$X = [X_M^T \ X_H^T]^T \quad (18+34=52 \text{ elements}) \quad (5)$$