

Design of Hydraulically Interconnected Suspension Systems for Tri-axle Straight Trucks with Rear Tandem Axle Bogie Suspensions

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ABSTRACT

This study has proposed a new roll-resistant hydraulically interconnected suspension (HIS) system for a tri-axle straight truck with rear tandem axle bogie suspension to suppress the roll motion of truck body. The equations of motion of the mechanical and hydraulic coupling system are established by incorporating the hydraulic forces as external forces into the mechanical subsystem, in which the hydraulic forces are derived using impedance transfer matrix method and related to the state vectors of mechanical subsystem at the boundaries.

Based on the derived equations of the coupling system, modal analysis method is employed to investigate the dynamic characteristics, including natural frequencies, mode shapes and dynamic responses. The results indicate that the proposed HIS system can effectively enhance the natural frequencies of truck body pitch and roll modes, and significantly increase the mode damping. The mode shapes of truck body are also changed. The study of dynamic response indicates that the amplitudes corresponding to the oscillation frequencies of truck body and wheel hop modes are heavily restrained. The proposed HIS system is also able to favorably adjust the dynamic load distribution among wheel stations. Furthermore, parametric analysis shows that natural frequencies of truck with HIS system depend on piston surface areas and installation schematics of actuators. Tire dynamic load coefficients can be favorably changed by adjusting the loss coefficients of damper valves.

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INTRODUCTION

It is well known that heavy trucks with higher location of center of gravity (CG), large weight and dimensions are more vulnerable to rollover than other types of vehicles, which are characterized by lower roll stability limits [1]. On the other hand, the road vehicle suspension design involves in a complex compromise among different performance indexes related to ride comfort and handling stability, as well as road friendliness [2,3]. Those performances are determined by the suspension modes [4], i.e. bounce, pitch, roll and warp, and reflected from dynamic responses of full-truck model. Therefore, the rollover prevention systems for heavy trucks, realized by enhancing the suspension roll mode, are able to improve the performances [5]. However, the mechanical antiroll bars in conjunction with leaf spring suspensions improve roll stability limit with sacrificing the ride comfort to some extent [6]. Recently, all kinds of active and semi-active roll control systems have been developed to improve the roll

stability [7,8,9]. However, it has been noted that some drawbacks are inevitably involved in these control techniques, such as increased cost, uncertain reliability, power consumption requirements, and inherent complexity [10]. To overcome the drawbacks mentioned above, some advanced suspension systems have been developed as alternative solutions to the active or semi-active suspensions in order to achieve a better compromise among the performances.

The passive hydraulically interconnected suspension (HIS) system has been reported to be able to supply many advantages that arise from its use besides it owning the normal functionality of conventional suspension systems, such as independently adjusting wrap stiffness and damping. To the best of the authors' knowledge, there have been a limited number of theoretical and experimental studies for HIS systems. For instance, Ortiz [11] conceptually integrated mechanical/hydraulic schematic to provide separate spring/damping for the pitch/bounce and roll/warp motions.

Fontdecaba [12] attempted to ideally implement a complete modal decoupling by independently adjusting wrap stiffness and damping levels via central suspension unit. Mace [13] theoretically studied a family of existing passive HIS systems using network theory and system synthesis methodologies, in which the suspension admittance matrices were defined based on the assumption of ideal interconnections. Smith [4] further investigated two- and six-wheel interconnection schemes to achieve the appropriate mode decoupling by independently adjusting stiffness/damping. In the studies of the above scholars, ideal interconnections are assumed, and thus ignored the pressure loss caused by transmission lines, so the dynamics of the interconnecting mechanisms were not investigated, which would limit the applicability of this method to complex HIS systems. In the work of Wilde [14], experimental and subsequent dynamic simulations show that turning stability of SUV equipped with HIS was significantly improved in reducing the roll angle and roll rate. Cao [15] studied the properties and dynamics characteristics of interconnected hydro-pneumatic suspensions in pitch-and-roll-plane, considering the pressure loss of hydraulic circuits and damper valves. The results showed that roll and pitch modal stiffness and damping were enhanced, while remaining the soft bounce and wrap modes. Zhang [16,17] analyzed the free and force vibration characteristics of SUV fitted with roll-resistant HIS system based on a simplified roll-plan half-vehicle model and the mathematic model was validated by experimental results. Both results indicated that HIS system can improve the roll stability without affecting bounce stiffness. Quite recently, Docquier [18] found that the HIS can increase roll stiffness, while maintaining a soft wrap behavior on uneven roads.

For an up-to-date review of HIS, the readers can refer to two recently published works by Cao [15], Smith [19]. However, it can be seen that the most of above studies didn't fully considered hydraulically fluid system in dynamics analysis. Furthermore, the dynamics analysis for the coupling of multi-body and hydraulically fluid subsystems have not thoroughly investigated, and so it is difficult to qualitatively study the influence of HIS system parameters on the full-vehicle performance. In particular, there are barely some studied for the dynamic characteristics of tri-axle straight trucks equipped with HIS system. So one aim of this study is to investigate the dynamic characteristics of tri-axle straight truck fitted with passive roll-resistant HIS system.

Previous study shows that high mounted single inverted leaf spring centrally pivoted tandem axle bogie suspension includes synchronous and asynchronous modes [20]. Hence, this mechanism may cause dynamic load fluctuations among the tandem axles subject to braking at high speed [21]. Besides, a typical unfavorable heavily rear-biased distribution of the roll stiffness will aggravate the yaw stability [22]. Therefore, the suppression of roll motion of truck body particularly benefits to the improvement of ride comfort and handling performance, which is achieved by stiffening roll mode via HIS in this paper. In this study, a general

formulation method for mechanical and hydraulic coupling system is proposed to derive the dynamic equations of a tri-axle straight truck with roll-resistant HIS system, followed by brief description of the original truck with conventional suspension and how the HIS system works. Based on the obtained dynamic equations, the eigenvalues and eigenvectors are identified with eigenvalue identification method. Comparison investigation is carried out between the trucks with conventional suspension and HIS system focusing on natural frequencies/mode shapes, isolation vibration performances and random responses in frequency domain.

MODEL DESCRIPTION OF ROLL-RESISTANT HIS SYSTEM

The simplified model is shown in Figure 1. The full vehicle model is linear and consists of one lumped sprung mass m with three degrees of freedom (DOFs) around its center of gravity (CG), e.g. heave (z), pitch (θ) and roll (ϕ), two walking beams with two rational DOFs (θ_L and θ_R) and three unsprung masses. Each unsprung mass with lumped mass m_i ($i = f, m, r$) and roll inertia I_i^ϕ has two vertical translation DOFs z_{ij} ($j = l, r$) relative to the sprung mass located at the left and right wheel hub centers. The sprung mass and walking beam are suspended by spring-damper systems. Specifically, the rear two spring-damper systems connect the rear two unsprung masses to the front and rear ends of walking beams, respectively. The spring-damper systems are characterized by linear spring rate k_{sij} and viscous damping c_{sij} . The tire damping is ignored in this simplified model. The simplified walking beam model has been evaluated as a substituent to the original tandem axle bogie suspension with inverted leaf spring [23].

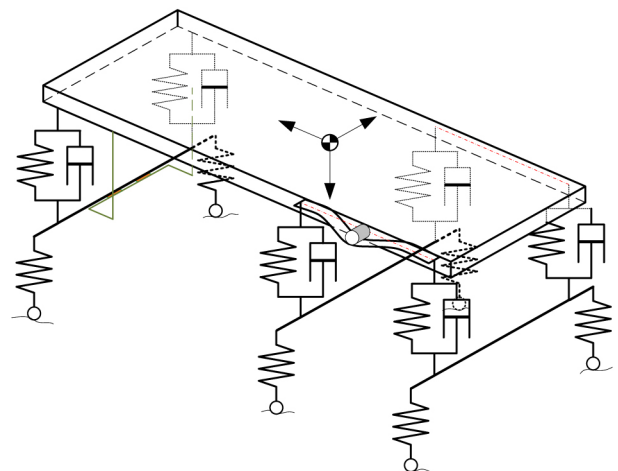


Figure 1. Full vehicle model for tri-axle straight truck

The actuators, realized by double-acting hydraulic cylinders, are mounted between the sprung mass and unsprung mass. When the vehicle in Figure 1 turn left, a positive roll motion between the sprung mass and unsprung

masses occurs, all the outer and inner suspensions are compressed and extended, respectively. Therefore, all the outer and inner cylinders head move downward and upward relative to their piston rods, respectively. It reduces the volume of the outer top and inner bottom cylinder chambers, and simultaneously increases the volume of the outer bottom and inner top cylinder chambers, as shown in Figure 2. Thus, the fluids in the former are squeezed into pipe lines and the latter accommodate more fluids from pipes lines. The volume differences in circuits I and II will result in outflow and inflow for the corresponding accumulators. As a result, the pressures of the circuits I and II are decreased and increased, respectively. It in return causes upward and downward resultant forces for all outer and inner actuators, respectively. Finally, a roll restoring moment is generated to prevent the roll motion of the sprung mass relative to the unsprung mass. As a result, the roll motion between the sprung mass and unsprung mass is reduced due to reaction force provided by this hydraulic system, which in turn alters the hydraulic force. This interaction will continue until a new equilibrium is reached.

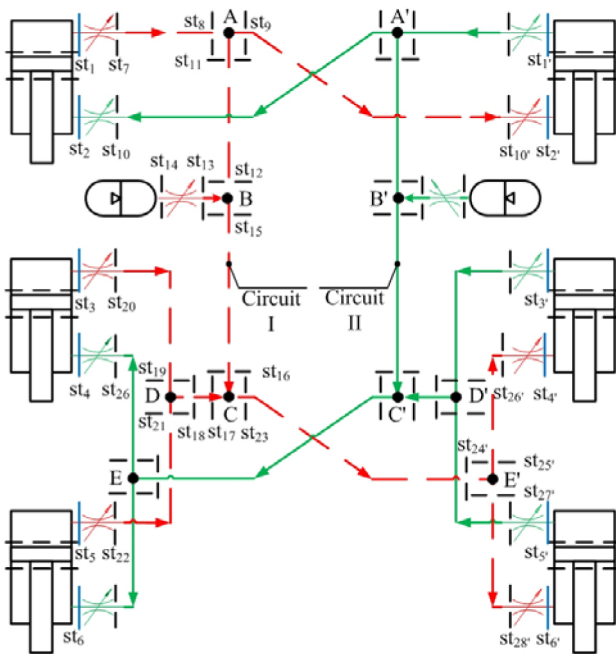


Figure 2. Fluid circuit for roll-resistant HIS* *It is denoted that the solid the dashed lines represent high and low pressure lines, respectively, when turned left.

As described the above, the integrated system is mechanical and hydraulic coupling system. Therefore, the investigation involves in developing the equations of motion for this coupling system. In this study, the dynamic equations of this system are separately established, and then integrated together to form the equations of motion at the boundary conditions.

MODELLING METHODOLOGY

Motion of Equations for Mechanical Subsystem

The equations of motion of the full-truck model are developed based on Newton's second law of motion, assisted by free-body-diagrams of rigid bodies on which the hydraulic forces are considered as external forces:

$$\mathbf{M}_U \ddot{\mathbf{x}} + \mathbf{C}_U \dot{\mathbf{x}} + \mathbf{K}_U \mathbf{x} = \mathbf{F}_W \mathbf{w} + \mathbf{F}_H \quad (1)$$

where $\mathbf{M}_U$, $\mathbf{C}_U$, $\mathbf{K}_U$ are the mass, damping and stiffness coefficient matrices, respectively. The displacement vector is defined as $\mathbf{x}_{11 \times 1} = [z \ \theta \ \phi \ \theta_j^T \ z_{ij}^T]^T$, in which θ_j and z_{ij} are the column vectors. $\mathbf{F}_W$ is the coefficient matrix corresponding to the road-disturbance input column vector $\mathbf{w} = [w_{ij}]^T$. The actuator forces $\mathbf{F}_H = \mathbf{D}_p \mathbf{P}$ are generated due to the pressures p_{ikj} ($k = U, B$) in the cylinder chambers, in which the pressure column vector $\mathbf{P} = [\mathbf{P}_I^T \ \mathbf{P}_{II}^T]^T$, where $\mathbf{P}_I = [p_{iU} \ p_{iBr}]^T$ and $F_{ij} = k_{ij}(z_{ij} - w_{ij}) + S_{iU}P$ are the pressure column vector for circuits I and II, respectively. $\mathbf{D}_p$ is the coefficient matrix.

Equations for Hydraulic Subsystem

Equation (1) indicates that the responses can be obtained if the relationships between $\mathbf{F}_H$ and $\mathbf{x}$ are determined. In fluid dynamics, the flow is related to flow rate with the effective flow area. In other words, the relationships between the flow and pressure determine the hydraulic forces $\mathbf{F}_H$, which are defined as flow impedance.

In Figure 2, four types of fluid components are included, such as nitrogen-filled diaphragm accumulator, three-way junctions, damper valves and fluid pipelines. Along the direction of the fluid flow, the connection section between different fluid components is marked as st_i . st_i' is the symmetrical section for st_i . A column vectors of the pressure and flow (p and q) at the in- or out-flow section (st_i or st_{i+1}) is referred to as state vectors $\mathbf{v}_i = [p \ q]_{st_i}^T$. The transfer matrix $\mathbf{T}^j$ is used to quantitatively relate the two state vectors for the j th component, so that, $\mathbf{v}_{i+1} = \mathbf{T}^j \mathbf{v}_i$, where the details of transfer matrices $\mathbf{T}^j$ for fluid components are given in [24]. The section marked with capital letters, such as A and A', denote where the flow mutation appears. Therefore, the fluid circuit between the adjacent flow-mutation sections is FCFC, and the transfer matrix between the two sections is defined as connectivity matrix $\mathbf{T}$ [24]. Besides, the transfer matrix for the junction B(B') with bypass accumulator is separately derived. Hence, nine connectivity matrices $\mathbf{T}_k$ ($k = 1, \dots, 9$) exist for each circuit. Figure 2 clearly shows circuits I and II are symmetrical. Therefore, the derivation of impedance for