

Property Analysis of an X-Coupled Suspension for Sport Utility Vehicles

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ABSTRACT

The influences of fluidic X-coupling of hydro-pneumatic suspension struts on the various suspension properties are investigated for a sport utility vehicle (SUV). The stiffness and damping properties in the bounce, pitch, roll and warp modes are particularly addressed together with the couplings between the roll, pitch, bounce and warp modes of the vehicle. The proposed X-coupled suspension configuration involves diagonal hydraulic couplings among the different chambers of the four hydro-pneumatic struts. The static and dynamic forces developed by the struts of the unconnected and X-coupled suspensions are formulated using a simple generalized model, which are subsequently used to derive the stiffness and damping properties. The properties of the X-coupled suspension are compared with those of the unconnected suspension configuration, in terms of four fundamental vibration modes, namely bounce, roll, pitch and warp, to illustrate the significant effects of fluidic couplings. The results suggest that the X-coupling could help achieve greater roll and pitch stiffness and damping, with negligible effects on the bounce and warp mode properties. It is further shown that the X-coupled struts offer greater design flexibility to achieve better compromise among different conflicting measures. From the results, it was concluded that the proposed X-coupling of the suspension struts could help achieve improved roll stability, handling and pitch control, without sacrificing the bounce ride quality and road-holding performance of SUVs during both the on- and off-road driving conditions.

INTRODUCTION

The suspension design of sport utility vehicles (SUVs) has been gaining considerable attention, due to the increasing popularity of the SUV market and concerns related to rollover risks [1-5]. SUVs exhibit relatively higher center of gravity (c.g.) and thus lower roll stability, when compared to light passenger cars [1, 2]. Moreover, such vehicles are expected to perform to a high standard over a wide range of road conditions (on- as well as off-road driving). These characteristics and performance requirements pose a very difficult challenge on the suspension design of SUVs, where a compromise

has to be achieved among the performance measures related to on- and off-road operations [1-3].

The design of a full-vehicle suspension system concerns four fundamental vibration modes, namely bounce, roll, pitch and warp [6-11]. The vertical ride quality generally necessitates soft bounce mode, while the relatively stiff roll and pitch modes would be beneficial for controlling vehicle attitude during steering and braking/traction maneuvers, and thus improved ride and handling qualities [12-14]. Moreover, it has been well accepted that the warp mode should be designed to be as soft as possible in order to improve the roadholding property [6-11]. These four modes of a conventional passive suspension, however, are strongly coupled.

The use of passive anti-roll bars could help achieve the roll stiffness independent of bounce/pitch properties in order to achieve improved vehicle roll stability. It, however, adds weight and also increases the warp mode stiffness, which is detrimental for roadholding property, particularly during off-road driving. While active anti-roll bars could achieve a better compromise among the various performance measures, their implementation is limited due to the added cost, weight and concerns related to reliability. It is thus desirable to explore alternative passive suspension mechanisms that permit independent tuning for all the four modes, or partial decoupling in a positive manner, so as to realize a better design compromise.

Passive interconnected vehicle suspensions have been explored, analytically and experimentally, in a number of studies [6, 8-10, 15-19]. These studies have invariably concluded that the passive interconnected suspensions could provide considerable potential to realize a full or partial decoupling among some of the modes. These studies also suggested that the fluidic interconnections, especially hydraulic, could enhance both the stiffness and damping properties in a very flexible manner. The fluidic interconnections can be conveniently realized in a suspension system involving hydro-pneumatic struts, which are regarded to hold the most significant potential for commercial vehicle applications [20-22]. The performance analyses of the suspensions with fluidic

interconnections, however, have been mostly undertaken in either roll or pitch plane.

In this study, a novel passive X-coupled hydro-pneumatic suspension is proposed and analyzed to investigate its potential for achieving decoupling of the concerned modes and an improved compromise among the conflicting performance measures of SUVs. The proposed suspension configuration involves diagonal hydraulic interconnections among the different chambers of the front- and rear-wheel hydro-pneumatic struts. The formulations of strut forces of the X-coupled suspension are developed and analyzed to derive suspension properties. The results attained from parametric analysis are also presented and discussed.

X-COUPLED HYDRO-PNEUMATIC SUSPENSION CONFIGURATION

Hydro-pneumatic suspension strut permits fluidic interconnections between different chambers of the struts in either the roll- or pitch-plane of the vehicle [15-17]. Figure 1 presents a schematic of the strut that integrates the gas chamber and damping valves within the same unit to realize a compact design. The shim disc valves are employed within the main piston to achieve variable resistance to flows between hydraulic fluid chambers 1 and 2. Additional damping orifices in the main piston connect hydraulic fluid chamber 1 and chambers 2 and 3. The floating piston isolates the hydraulic fluid in chamber 2 from nitrogen gas in chamber 4. The compact strut design provides considerably larger effective working area when compared to those reported in the literature [6, 18, 19], and thus helps reduce the operating pressure.

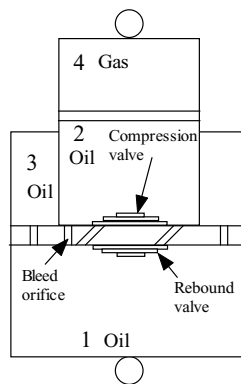


Fig. 1: Schematic of a hydro-pneumatic strut with integrated damping valves.

Figure 2 illustrates the proposed X-coupling of the front- and rear-wheel suspension struts, referred to as B_X . The proposed configuration involves couplings between the hydraulic fluid chambers 1 and 3 of the four suspension strut units, as shown. Chambers 1 and 3 of rear-left strut are coupled to 3 and 1 of the front-right strut, respectively, and are referred to as $1rl3fr$ and $3rl1fr$. In a similar manner, the chambers 1 and 3 of the rear-right strut are coupled to 3 and 1 of the front-left strut, respectively, and are referred to as $1rr3fl$ and $3rr1fl$. For

relative analysis of properties, an unconnected suspension arrangement, referred to as B_U , consisting of four suspension struts of the full vehicle suspension system, is also considered. Both suspension arrangements employ struts with identical geometry and charge pressure. The parameters related to damping properties of the two arrangements, however, differ, due to additional flow resistances of the connecting pipes in the B_X configuration.

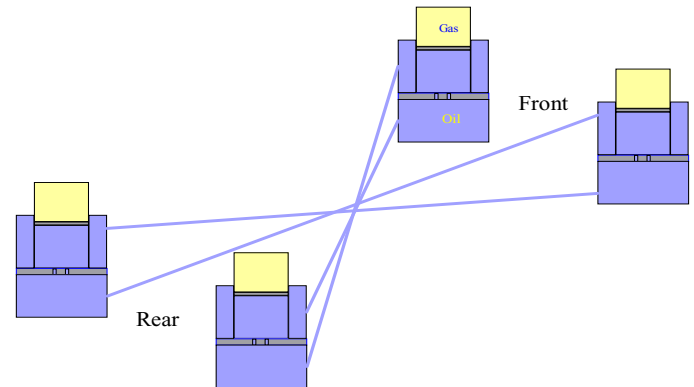


Fig. 2: Representation of the X-coupled hydro-pneumatic suspension (B_X).

FORMULATIONS OF STRUT FORCES AND PROPERTIES

Although the X-coupled suspension B_X involves complex fluid flows across front and rear as well as left and right suspension struts, the forces developed by each strut can be conveniently derived using a generalized model, presented in [15]. The model permits the evaluation of restoring and dissipative suspension forces due to hydro-pneumatic struts, unconnected or interconnected in the roll or pitch plane.

The primary assumptions for the modeling include: (a) turbulent flows through damping orifices between the hydraulic chambers within the same strut; (b) laminar flows through hydraulic interconnections between the connected struts; (c) polytropic gas process; (d) incompressible hydraulic fluid; (e) negligible leakage flows; (f) negligible thermal expansion of the struts and hydraulic fluid; (g) negligible friction between piston and cylinder; and (h) negligible floating piston dynamics. It has been shown that the bulk modulus of the hydraulic fluid is quite large, and the consideration of fluid compressibility yields only negligible effects on the stiffness properties [17].

The forces developed by the unconnected suspension struts (B_U) are identical to those derived in [16], while those developed by the X-coupled struts depend upon flows through interconnecting pipes and the feedback effects in a complex manner. The forces developed by the front-left (fl) and -right (fr) struts in the X-coupled suspension (B_X) are derived as:

$$F_f = P_0 \left[A_{1f} \left(\frac{V_{40f}}{V_{40f} + A_{1f}\dot{x}_f - A_{3r}\dot{x}_r} \right)^n - A_{3f} \left(\frac{V_{40r}}{V_{40r} + A_{1r}\dot{x}_r - A_{3f}\dot{x}_f} \right)^n \right] - P_0 A_{2f} - \frac{\rho A_{1f} |A_{1f}\dot{x}_f - A_{3r}\dot{x}_r| (A_{1f}\dot{x}_f - A_{3r}\dot{x}_r)}{2C_d^2 a_{12f}^2} - \frac{128\mu L A_{3f}^2 \dot{x}_f}{\pi D^4} + \frac{\rho A_{3f} |A_{1r}\dot{x}_r - A_{3f}\dot{x}_f| (A_{1r}\dot{x}_r - A_{3f}\dot{x}_f)}{2C_d^2 a_{12r}^2} \quad (1a)$$

Where $r=rr$ for the front-left strut ($f=fl$), and $r=rl$ for the front-right strut ($f=fr$).

The forces developed by the rear struts are also expressed in a similar manner, as:

$$F_r = P_0 \left[A_{1r} \left(\frac{V_{40r}}{V_{40r} + A_{1r}\dot{x}_r - A_{3f}\dot{x}_f} \right)^n - A_{3r} \left(\frac{V_{40f}}{V_{40f} + A_{1f}\dot{x}_f - A_{3r}\dot{x}_r} \right)^n \right] - P_0 A_{2r} - \frac{\rho A_{1r} |A_{1r}\dot{x}_r - A_{3f}\dot{x}_f| (A_{1r}\dot{x}_r - A_{3f}\dot{x}_f)}{2C_d^2 a_{12r}^2} - \frac{128\mu L A_{3r}^2 \dot{x}_r}{\pi D^4} + \frac{\rho A_{3r} |A_{1f}\dot{x}_f - A_{3r}\dot{x}_r| (A_{1f}\dot{x}_f - A_{3r}\dot{x}_r)}{2C_d^2 a_{12f}^2} \quad (1b)$$

Where $f=fl$ for the rear-right strut ($r=rr$), and $f=fr$ for the rear-left strut ($r=rl$).

In the above formulations, F_i is the dynamic force developed by strut i ($i=fl, fr, rl, rr$), A_{ji} is the effective piston area reflected on the chamber j ($j=1,2,3$) side of the strut i , P_0 is the static charge pressure, x_i and $\dot{x}_i$ are the relative displacement and velocity across the strut i , respectively, assuming small motions with positive direction being upward. V_{40i} is the initial volume of gas in chamber 4 of strut i , C_d is the discharge coefficient, ρ is mass density of the hydraulic fluid, μ represents the dynamic viscosity of hydraulic fluid, and L and D represent the length and diameter of the interconnecting pipes, respectively. a_{12i} is the effective orifice area due to bleed orifices and damping valves of strut i . The above equation clearly shows that hydraulic interconnections in the X-coupled suspension exhibit strong couplings in the stiffness as well as damping terms.

The variations in damping forces could be realized by varying the effective flow areas of damping valves. Modeling of damping variations in a piecewise-linear manner [23] would yield non-differential variations in the fluid pressures in the vicinity of the transition pressures, a refined model has thus been used to smoothen the flow variations around the transition region [17]. Asymmetric damping force in compression/rebound motions could be achieved by selecting different flow areas, threshold values and maximum pressure differentials in compression (P_{csl} , P_{csh}) and extension (P_{esl} , P_{esh}), such that:

$$a_{12i} = \begin{cases} a_{12c} & -P_{esl} \leq P_{12i} \leq P_{csl} \\ a_{12c} + a_{12vc} \left\{ \frac{(P_{12i} - P_{csl})}{P_{csh} - P_{csl}} - \frac{1}{2\pi} \sin \left[\frac{2\pi(P_{12i} - P_{csl})}{P_{csh} - P_{csl}} \right] \right\} & P_{csl} < P_{12i} \leq P_{csh} \\ a_{12c} + a_{12vc} & P_{12i} > P_{csh} \\ a_{12c} + a_{12ve} \left\{ \frac{(P_{12i} - P_{esl})}{P_{esh} - P_{esl}} - \frac{1}{2\pi} \sin \left[\frac{2\pi(P_{12i} - P_{esl})}{P_{esh} - P_{esl}} \right] \right\} & P_{esl} < P_{12i} \leq P_{esh} \\ a_{12c} + a_{12ve} & P_{12i} > P_{esh} \end{cases} \quad (2)$$

where a_{12c} is the bleed orifice area, a_{12vc} and a_{12ve} are the maximum effective flow areas of valves in compression and rebound, respectively. P_{csl} and P_{esl} are the lower limits of pressure differentials in compression and rebound, which cause deflections of shim discs to initiate valve opening, and P_{csh} and P_{esh} are the pressures that cause maximum valve openings, namely a_{12vc} and a_{12ve} . The symmetric damping can be easily achieved by letting: $P_{csl}=P_{esl}$, $P_{csh}=P_{esh}$ and $a_{12vc}=a_{12ve}$.

STIFFNESS PROPERTIES

The properties of road vehicles suspensions can be evaluated using two different approaches [15-17, 19, 24, 25]. An analytical approach based upon coupled vehicle vibration modes of a vehicle, e.g. roll and bounce, in an ideal manner that neglects the influence of structural deflection modes and suspension kinematics, has been used to determine the stiffness and damping rates of the suspension [15-17, 19]. This approach considers the entire vehicle motions and is quite sensitive to variations in vehicle inertial and geometry parameters. An alternative approach assumes a fixed vehicle frame (sprung mass) to reduce the contributions of coupling among various vibrations modes of the vehicle body and thus facilitate the determination of stiffness properties of the suspension in individual modes [24, 25]. This method can be considered to be more suspension-oriented, and less sensitive to variations in vehicle mass parameters. Moreover, this approach is far simpler than the former method, due to absence or reduction in coupling of the vehicle vibration modes.

The first evaluation method based upon the coupled vehicle dynamics may be more theoretically accurate, considering the strong coupling effects of vibrations modes of the vehicle with nonlinear suspension [3]. It has been used to develop and analyze properties of either the roll- or pitch-plane connected suspension arrangement [15-17, 19]. However, it may not be efficient for evaluating a full vehicle suspension system, which involves very complex coupling among the bounce, roll, pitch and bounce modes. Therefore, the second method that assumes a fixed vehicle frame is used in this study to evaluate relative properties of the uncoupled and X-coupled hydro-pneumatic suspension configurations.