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# Characterization of a hydro-pneumatic suspension strut with gas-oil emulsion

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ABSTRACT

The nonlinear stiffness and damping properties of a simple and low-cost design of a hydro-pneumatic suspension (HPS) strut that permits entrapment of gas into the hydraulic oil are characterized experimentally and analytically. The formulation of gas-oil emulsion is studied in the laboratory, and the variations in the bulk modulus and mass density of the emulsion are formulated as a function of the gas volume fraction. An analytical model of the HPS is formulated considering polytropic change in the gas state, seal friction, and the gas-oil emulsion flows through orifices and valves. The model is formulated considering one and two bleed orifices configurations of the strut. The measured data acquired under a nearly constant temperature are used to identify gas volume fraction of the emulsion, and friction and flow discharge coefficients as functions of the strut velocity and fluid pressure. The results suggested that single orifice configuration, owing to high fluid pressure, causes greater gas entrapment within the oil and thus significantly higher compressibility of the gas-oil emulsion. The model results obtained under different excitations in the 0.1–8 Hz frequency range showed reasonably good agreements with the measured stiffness and damping properties of the HPS strut. The results show that the variations in fluid compressibility and free gas volume cause increase in effective stiffness but considerable reduction in the damping in a highly nonlinear manner. Increasing the gas volume fraction resulted in substantial hysteresis in the force–deflection and force–velocity characteristics of the strut.



## 1. Introduction

Hydro-pneumatic suspensions (HPS), owing to their compact design and superior design flexibility, are increasingly being implemented in commercial road and off-road vehicles [1–5]. Their nonlinear pneumatic-stiffness and hydraulic-damping properties could provide enhanced attenuation of ride vibrations under large payload variations [4,6], while offering improved handling performance through cross-axle interconnections [7,8] or control interventions [9,10]. Various designs of the HPS struts have evolved over the past few decades, which generally comprise a number of gas and oil chambers [7,11,12]. The strut chambers containing hydraulic oil are usually coupled via bleed orifices and/or damping or check valves.

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The gas may be separated from oil by a floating piston [7,13] or a diaphragm [11], or the gas and oil may be contained within the same chamber [12,14].

The separation of the gas from the oil via a floating piston or a diaphragm requires additional chambers within the strut and increases the design complexity and cost of the HPS strut. Struts with chambers shared by the gas and oil may offer low cost and simpler designs. Such a design, however, permits gas entrapment within the oil and may yield highly complex variations in stiffness and damping properties of the strut. The entrapment of gas in the oil results in gas-oil emulsion within the strut leading to greater variations in the gas and oil properties, namely, the mass density and bulk modulus [15–17]. During operation, the gas-oil emulsion may also occur in high pressure struts with separated gas and oil chambers due to releasing/dissolving of gas in the oil as well as leakage through the floating piston seals [11]. This tends to alter the suspension performances, which has not been thoroughly investigated. Characterization of the HPS systems thus necessitates considerations of the effects of gas-oil emulsion, which could provide important design guidance for the HPS struts.

The characteristics of the HPS systems with separated oil and gas chambers have been investigated in a number of studies, while considering nominal gas and hydraulic oil properties [11,13,18]. The stiffness and damping coefficients of a HPS strut generally increase with increasing gas pressure and strut velocity, respectively. Els and Grobbelaar [13] analyzed a HPS strut with two oil chambers and a separated gas chamber. The strut damping effect was shown to increase the strut temperature in a laboratory test, which resulted in relatively greater strut stiffness and ride height. During the field test, the oil temperature saturated at about 85 °C, although only negligible variation in gas temperature was observed due to good heat dissipation of the gas chamber. The reported laboratory results also revealed approximately adiabatic gas process under sinusoidal excitations at relatively higher frequencies. It was suggested that the heat transfer between the gas and its surroundings should be considered at relatively lower frequencies (<0.5 Hz). Van Der Westhuizen and Els [19] compared the results obtained from real gas equations considering the heat transfer with the ideal gas law. Ideal adiabatic approach was shown to be appropriate within excitation cycles at relatively higher strut velocities. Moreover, relatively higher hysteresis was observed in the gas pressure measured at lower excitations frequencies compared to the higher frequencies, which was attributed to the heat transfer and thereby additional contribution to the energy dissipation of the HPS strut [13,19].

Guo et al. [11] and Küçük et al. [20] analyzed the HPS strut comprising three oil chambers and a separated gas chamber assuming adiabatic gas process, turbulent fluid flows through the orifices and check valves, and negligible leakage flows. The three oil chambers, however, involved complex fluid flows among them and one of the chambers approached vacuum at a high velocity, as reported by Guo et al. [11]. Cao et al. [18] proposed an analytical model of a twin-gas-chamber HPS strut design with two gas chambers and two oil chambers. This novel HPS strut offered greater effective working area than the conventional strut designs and thereby relatively lower operating pressure for a given load capacity. The twin-gas-chamber design also revealed relatively lower asymmetry in the suspension rates during compression and extension.

In comparison to the struts with separated gas and oil chambers, only a few studies have explored the properties of strut designs with chambers shared by both the gas and the hydraulic oil. Yang et al. [12] and Shen et al. [14] analyzed a HPS strut with one mixed gas-oil chamber and an oil chamber. The studies reported hardening tendency in stiffness and reduced damping force during compression. Shen et al. [14] investigated the effect of varying the bleed orifices size, while Yang et al. [12] suggested that the variations in oil temperature affected the HPS properties only slightly. The effects of gas and oil mixing on the strut properties, however, were neglected in these studies. Within the mixed gas-oil chamber, the entrapped gas has been reported to dissolve into the oil and/or exist as gas bubbles [15]. The resulting gas-oil emulsion possesses lower mass density and bulk modulus compared to those of the hydraulic oil, which may affect the rates of fluid flows and effective volumes of the gas and the fluid. When considerable gas is entrapped within the hydraulic oil, the bulk modulus of the emulsion may be significantly reduced and highly sensitive to the fluid pressure [16,17]. The properties of the mixed fluid such as bulk modulus and mass density are strongly influenced by the gas volume fraction, which have not yet been adequately addressed.

Furthermore, the aforementioned studies have generally assumed Coulomb [19] or negligible [18,20] seal friction within the HPS strut. Owing to the high pressure design, the sealing of the gas chamber from the oil chamber generally involves substantial seal friction. The magnitude of the seal friction may be significant compared to the hydraulic damping force at a relatively lower velocity [19]. Various friction models have been proposed for characterizing seal friction considering pre-sliding hysteresis, stick–slip and Stribeck effects [21–23]. It would be worthy to investigate the significance of seal friction on the HPS characteristics over a range of strut operating velocity.

In this study, the characteristics of a simple and low cost HPS strut design with one mixed gas-oil chamber and one separate oil chamber are experimentally and analytically investigated. The static and dynamic pressure/force–deflection and force–velocity properties of a prototype strut are characterized in the laboratory under a nearly constant temperature, in the 0.1 to 8 Hz frequency range with peak velocity ranging from 0.05 to 0.24 m/s. An analytical model is formulated considering the seal friction, polytropic change in the gas state, entrapped gas within the hydraulic oil, mixed fluid flows through the bleed orifices and the check valves. The model validity is subsequently examined using the measured fluid pressures within the two strut chambers and the total strut force over the range of excitation velocities. The measured data and the model are analyzed and discussed to highlight the effects of gas-oil emulsion on the stiffness and damping properties of the HPS strut.