

Effects of Entrapped Gas within the Fluid on the Stiffness and Damping Characteristics of a Hydro-Pneumatic Suspension Strut

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ABSTRACT

This study is aimed at characterizing the nonlinear stiffness and damping properties of a simple and low cost design of a hydro-pneumatic suspension (HPS) that permits entrapment of gas into the hydraulic fluid. The mixing of gas into the oil yields highly complex variations in the bulk modulus, density and viscosity of the hydraulic fluid, and the effective gas pressure, which are generally neglected. The pseudo-static and dynamic properties of the HPS strut were investigated experimentally and analytically. Laboratory tests were conducted to measure responses in terms of total force and fluid pressures within each chamber under harmonic excitations and nearly steady temperature. The measured data revealed gradual entrapment of gas in the hydraulic fluid until the mean pressure saturated at about 84% of the initial pressure, suggesting considerably reduced effective bulk modulus and density of the hydraulic fluid. An analytical model of the HPS strut was formulated considering polytropic change in the gas state and increased fluid compressibility due to entrapped air. Both the measured data and the model results showed progressively hardening stiffness of gas during compression, while the damping effect attributed to fluid flows between different chambers was higher during strut rebound. The results further suggested that 20% decrease in fluid density and effective bulk modulus will result in about 18% decrease in the equivalent damping coefficient and 2% decrease in the equivalent stiffness. The reduction in mean strut pressure would also yield relatively higher static deflection of the HPS strut, which could necessitate an additional height adjustment mechanism.

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INTRODUCTION

Machine operators working in the agriculture, construction and mining sectors are known to experience excessive levels of whole-body vibration, which is mainly arising from the large tire interactions with the off-road rough terrain [1, 2, 3]. The hydro-pneumatic suspensions (HPS), owing to their compact designs and design flexibility, are increasingly being implemented in off-road machines for enhancement of ride vibration performance under large payload variations [4, 5, 6]. Various designs of HPS struts have evolved over the past few decades, which generally comprise several gas and oil chambers [7, 8, 9]. The gas chamber serves as a nonlinear spring, and the oil flows across oil chambers and friction within the strut contribute to the damping feature of the suspension system. In these designs, the gas may be separated from the oil by a floating piston [9] or a diaphragm [7], or the gas and oil may be contained within the same chamber [8,10]. The separation of the gas from the oil requires more chambers within the strut and thus increases design complexity and cost of the HPS strut. Struts with chambers shared by gas and oil may offer low cost and simple designs but yield highly

complex variations in stiffness and damping properties. During operation, the entrapment of gas within the oil occurs leading to greater variations in the gas and oil properties. These tend to alter the suspension performance, which has not been thoroughly investigated. The entrapment of gas may also occur in the high pressure struts with separated gas and oil chambers due to leakage through the separating piston or diaphragm [7], thus affecting suspension performance. Characterization of the properties of HPS systems thus necessitates considerations of the effects of entrapped gas within the oil on their stiffness and damping characteristics, which could serve as important design guidance for the HPS struts.

The characteristics of the HPS systems have been investigated in a number of studies while considering nominal gas and oil properties, when the gas chamber is separated from the oil chambers [7,11,12]. Els and Grobbelaar [11] and Sun et al. [13] have analyzed a HPS strut with a separate gas chamber and two oil chambers coupled via bleed orifices and check valves. The stiffness and damping coefficients of the HPS were shown to increase with increasing gas pressure and

velocity of the strut, respectively. The hardening stiffness characteristics of such struts are considered beneficial for wide payload variation encountered in off-road machines, while the increasing damping coefficient may not be favorable for attenuation of vibration in the critical ride frequency range. The suspension damping during strut compression was designed to be lower than that during rebound in order to limit the bounce vibration transmission as in typical automotive suspension dampers [14]. Els and Grobbelaar [11] have also investigated the heat transfer and the effects of temperature variation on the HPS strut. The heat dissipation of the gas was shown to cause hysteresis in the gas pressure, while the influence on damping was shown to decrease with the increase in excitation frequency, which was attributed to reduced time for the heat transfer. Guo et al. [7] analyzed a HPS strut with one separated gas chamber and three oil chambers, and demonstrated that the stiffness and damping characteristics were similar to those in [11] and [13]. The three oil chambers, however, involved complex oil flows among them and one of the chambers experienced vacuum at a high velocity. Cao et al. [12] proposed an analytical model of a twin-gas-chamber HPS strut design with two gas chambers and two oil chambers, which offered a greater effective working area than conventional strut designs [15] and thereby relatively lower operating pressure for a given load capacity. The results showed less aggressive hardening and softening behaviors in the bounce stiffness compared to the strut with single gas chamber.

In comparison to the struts with separated gas and oil chambers, only a few studies have explored the properties of strut designs with mixed gas and oil chambers. Yang et al. [8] and Shen et al. [10] attempted a HPS strut with one mixed-gas-oil chamber and an oil chamber which is widely implemented in mining trucks due to its simple design. The strut comprised two chambers coupled by bleed orifices and check valves, in which one of the chambers contained both gas and oil. The effects of mixing the gas and oil, however, was neglected. The entrapped gas within the oil has been reported to increase the volume of the mixed fluid, and thereby lead to reduced fluid bulk modulus and fluid density [7, 16]. The studies also reported hardening tendency in stiffness and reduced damping force during compression. Shen et al. [10] investigated the effect of varying the size of bleed orifices, and showed increase in pressure difference and damping forces with lower orifice size. Yang et al. [8] further suggested that the variation of oil temperature affected the HPS properties only slightly.

In this study, the stiffness and damping properties of a simple and low cost HPS strut design with one mixed-gas-oil chamber and one separate oil chamber are investigated analytically and experimentally. An analytical model, is formulated considering polytropic change in the gas state and fluid compressibility, and validated using the measured data. The measured data and the model are then analyzed and discussed to highlight the nonlinear effects of entrapped gas within the oil, and the resulting variations in equivalent stiffness and damping coefficients of the HPS strut.

STRUT DESIGN AND MODEL FORMULATION

The hydro-pneumatic suspension (HPS) strut, considered in this study, comprises two chambers connected via bleed orifices and check valves, as illustrated in Fig. 1. The piston-side chamber contains both the gas and oil, and the annular rod-side chamber contains only oil. The oil can flow from the piston-side chamber to the rod-side chamber via the check valves and bleed orifices on the strut rod during compression, while the check valves remain closed during the rebound. The volume of the oil within the strut ensures that the check valves and bleed orifices remain submerged in oil within the range of strut travel. The oil flow through the valves and orifices between the two strut chambers contributes to the damping force, while the restoring force is developed by the gas [12, 13]. The initial volume and pressure of the gas is selected to achieve desired load capacity and the spring rate considering the cross-section areas of the piston and the rod. Moreover, the rod of the HPS strut can also serve as the kingpin for the steering system leading to compact suspension design for off-road machines.

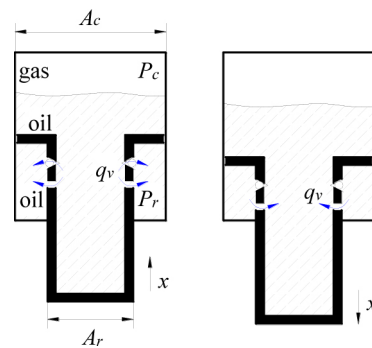


Figure 1. Schematic of the hydro-pneumatic suspension (HPS) strut

Considering the friction due to the seals between the strut cylinder and strut rod, the total force developed by the HPS strut can be obtained from:

$$F = P_c A_c - P_r (A_c - A_r) + f \quad (1)$$

where P_c and P_r are pressures of fluids within the piston-side and rod-side chambers, respectively; A_c and A_r are effective areas of the piston and rod, respectively; and f is the friction force due to hydraulic seals.

The instantaneous pressures of the gas and oil within the piston-side chamber are assumed to be identical neglecting the fluid inertia. Assuming polytropic process of the gas, P_c can be obtained from the initial gas charge pressure P_0 and volume V_{g0} , and the instantaneous gas volume V_g^r , such that:

$$P_c V_g^r = P_0 V_{g0}^r \quad (2)$$

where r is the polytropic exponent. The pressure within the rod-side chamber strut is derived considering the compressibility of the oil on the basis of the continuity equation, which can be expressed as: