INFLUENCE OF HOUSING WALL COMPLIANCE ON SHOCK ABSORBERS IN THE CONTEXT OF VEHICLE DYNAMICS

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Abstract. Shock absorbers play a key role in vehicle dynamics. Researchers have spent significant effort in order to understand phenomena associated with this component, but there are still several issues to address, in part because new technology development and design trends continually lead to new challenges, among which weight reduction is crucial. For shock absorbers, weight reduction is related to the use of new materials (e.g. composite) or new design paradigms (e.g. more complex geometry, wall thickness, etc.). All of them are directly linked to wall compliance values higher than the actual ones. The present article proposes a first analysis of the phenomena introduced by a high wall compliance, through a modelling approach and various simulations in order to understand the vehicle behaviour changes. It is shown that high values of wall compliance lead to increased hysteresis in the force-velocity curve. However, comfort, handling and ride performances are not significantly affected by this designing parameter.

1. Introduction
Shock absorbers reduce the amplitude of vibrations of the sprung and unsprung masses by dissipating the energy arising from suspension motion. Furthermore, they control the rate of weight transfer during transient vehicle behavior (braking, corner entry and acceleration). These duties make them fundamental sub-systems of most vehicles [1].

In order to accomplish their role, they exploit viscous friction between the hydraulic fluid and solid components. The phenomena associated with this component are very complex, making their study challenging from a scientific point of view. Several of these phenomena have already been studied and characterized (for instance [2–5]), nevertheless a significant effort is needed to address the ones related to the latest technology development and design trends, such as weight reduction. Less mass leads to lower fuel consumption and energy saving, both fundamental topics for current research [6,7]. In the case of shock absorbers, weight reduction could be obtained through the use of new materials (e.g. composite materials, polymers) and also through new design paradigms such as high housing walls compliance (which, depending also on mechanical properties, is indirectly related to new materials too).

Several kinds of shock absorbers are available for automotive applications with twin-tube shock absorbers being the most common [1], and their detailed modeling is quite complex and does not attend the needs of the presented work. Therefore, the authors focus on a more simple through-rod
shock absorber (which is also found in automotive application, e.g. [8]). Various simulations are carried out to compare their behaviors and to understand how the walls compliance affect vehicle dynamics.

The next section describes the methodology used for modeling shock absorbers (section 2), followed by simulations and their results (section 3), closing with conclusions and indications for future works (section 4).

2. Methodology

The walls compliance of a generic hydraulic chamber whose volume is forced to change due to external phenomena can be defined from the equation [13]:

\[ V(p, T) = (V_0 + \sum V_i)[1 + wc(p - p_{sat})] \]  

representing the volume of the chamber in function of the induced volume variations \( \sum V_i \) and in function of internal pressure \( p \) and external pressure \( p_{ext} \). The term \( V_0 \) is the initial volume and \( wc \) is the chamber wall compliance, the last one taken constant. With respect to an infinitely stiff shock absorber, the one with \( wc \neq 0 \) has an increased volume (the increase is equal to \( wc(p - p_{ext}) \) which lead to pressure changes in each chambers, due to the relation between pressure and density expressed by [13]:

\[ \rho(p) = \rho(0)e^{\frac{p}{B_{\text{fluid}}(p_{sat})}} \]  

with \( \rho \) density and \( B_{\text{fluid}}(p_{sat}) \) fluid isothermal bulk modulus at saturation pressure.

The wall compliance is calculated assuming the volume variation of the hydraulic chamber equal to the one of an infinitely long tube with thin wall, thus neglecting any increase of volume in the axial direction and any border effects at the interface between lateral and top/bottom walls. \( wc \) is the same for both top and bottom hydraulic chambers.

Shock absorbers have been modelled in the LMS ImagineLab AMESim environment, according to the scheme in figure 1. AMESim has been choose due to its ability in reproducing high nonlinear system with accuracy and allowing, at the same time, a significant save of time due to its computation efficiency [9]. Furthermore, several studies on shock absorber made use of this tool (for instance [8–12]), which can be considered validated by the scientific community. Models have linear valves with cracking pressure \( p_{crack} \) (which is the pressure necessary to lift the disc valve), leakage with viscous friction and wall compliance. For details about the equations refer to the AMESim help manual [13].

Two geometrically identical models of shock absorber with different valves parameters have been used for the rear and front suspension systems. The different valves parameters lead to different damping behaviour. Each simulation is carried out twice, varying only the wall compliance value of hydraulic chambers in shock absorber models (“low” and “high” wall compliance). The “low wall compliance” is obtained with steel mechanical properties, while the “high wall compliance” is roughly ten times higher (for all the models \( wc \) is equal in both bottom and top hydraulic chambers).

3. Simulations

Several simulations were carried out in order to have a broad view of the shock absorber behaviour and its influence in the full vehicle dynamics when \( wc \) significantly change.

3.1. Force-velocity curve analysis

One of the most common way to characterize shock absorbers is through the force-velocity curve. To obtain it, the piston rod is forced to move with an imposed velocity (in the direction of its axis). The force produced by the shock absorber is then plotted in function of the velocity itself [1].
Figure 1: AMESim model.

Figure 2 shows the central area of the force-velocity curve of the two models (front suspension couple) obtained with a sinusoidal input (amplitude 1 m/s, frequency 1 Hz). The increased hysteresis for the high wall compliance model is clearly visible in figure 2(b).

![Force velocity curve](image)

(a) Force velocity curve. (b) Zoom in the low velocity area.

Figure 2: Force-velocity curve obtained at 0.6 m/s, 1 Hz.

The hysteresis is mainly caused by a delay in time-domain of some physical quantities responses to the input [14]. Among these quantities, pressures in both chambers play a significant role, because their difference is the main responsible of the reaction force developed by the shock absorber itself. Figure 3 shows pressure variation in both chambers for different amplitude of the input. The nonlinear behaviour of the shock absorber and its amplitude dependence are clear in the figure. The crucial differences between the two models (high and low wall compliances) are the delay in time domain (already clear from the increased hysteresis) and the maximum and minimum values of pressure reached. In a real component, the lower pressures in the high wall compliance model would be reason of lower mechanical stress in real applications, therefore might slightly affect the design.

Pressure difference is also related to the reaction force \( F \), which is linked to the rod velocity \( v \) and to the average damping coefficient \( c_d \) by the following relation:

\[
F = c_d v. \tag{3}
\]

In theory \( c_d \) should be different in the two models (due to diverse pressure difference). However, the maximum (minimum) forces reached difference are negligible, thus \( c_d \) can be considered constant.
Lastly, several parameters characterizing the fluid are pressure-dependent, thus measurable changes between the two models are present. Despite the difference relative to the variation is significant, most of the variables characterizing the fluid can be considered constant during the entire simulation. For example, the bulk modulus is shown in figure 4.

3.2. **K&C test bench simulation**

In order to simulate the effect of an increased wall compliance in operative conditions, a K&C test has been simulated. A multi-body model of a McPherson suspension system has been modelled in AMESim, including:

- shock absorber;
- spring;
- spindle;
- lower wishbone;
- steering tie rod;
- steering rack;
- bushing (between strut and body, lower wishbone and body).

All the bodies are rigid. Input used to simulate the K&C test are:

- wheel vertical motion;
rack motion;
force (x and y direction) and moment (x, y and z direction) at wheel centre.

At first, lateral rack displacement was the predominant (motion) input, then it was wheel vertical motion. Figure 5(a) shows lateral (Y-axis) and vertical (Z-axis) wheel centre location in function of time, making clear when the vertical displacement assumes a predominant role; lateral displacement is always present due to interactions between rigid bodies. Forces produced by the two shock absorber models have been collected and confronted. Figure 5(b) shows a difference lower than 1% in the two cases.

(a) Wheel centre absolute position in function of time. (b) Comparison of vertical forces at piston.

Figure 5: Selected inputs (a) and results (b) of K&C simulation.

3.3. Comfort characterization
Results of section 3.1 and 3.2 indicate that an increased wall compliance does not lead to significant changes into the operative behaviour of the shock absorber and of the suspension system. Nevertheless, this aspect is also investigated to evaluate the impact of high wall compliance into the full vehicle dynamic behaviour. At first, comfort has been studied, making use of the 7DOFs car model of AMESim. Performance in this context is characterized through the frequency response of pitch velocity and of (centre of gravity) vertical acceleration to sine wave inputs. Results for high and low wall compliance models are very similar and do not present relevant differences (figure 6 shows pitch angle response).

3.4. Ride and handling manoeuvres
Lastly, several manoeuvres done by car manufacturers have been simulated to evaluate the car behaviour for ride and handling purpose, focusing on several characteristics, among which:

- the car body yaw velocity rate in function of longitudinal velocity, evaluated during a manoeuvre with constant steering angle and increasing speed;
- over-steering at wheel, evaluated during a quasi-static steering manoeuvre in which the velocity is constant;
- the roll rate, which is also analysed during the quasi-static steering manoeuvre;
- steering torque during all the manoeuvres.

The 18DOFs AMESim full vehicle model has been used. Even in this case, all the more relevant metrics did not show any significant difference.
4. Conclusions

Nowadays, thanks to new materials and advanced topology optimization techniques, it is theoretically possible to obtain values of walls compliance higher than reachable in the past, which is the main reason behind this study. In shock absorbers, high values of \( w_c \) would allow to reduce their weight, thus leading to a series of advantages such as less consumption and pollution, better performance in terms of sport driving. The aim of this study is to analyse the effect of \( w_c \) on the behaviour of shock absorbers and on vehicle dynamics through a simulation approach, in order to investigate eventual side effects that might compromise vehicle performance. Simulations have been chosen as a tool for this study because they allow to reduce both costs and time by avoiding the use of prototype and test campaign. The authors used the LMS ImagineLab AMESim environment due to its performance when studying nonlinear multiphysical system composed by several sub-components, such as shock absorbers. Furthermore, its tools, models and techniques have already been validated by the scientific community. This tool allow to study complex nonlinear

The force-velocity curve has been calculated for two shock absorber models different only for \( w_c \), showing that an increased housing walls compliance leads to a higher hysteresis in the force-velocity curve. Furthermore, some physical quantities characterizing the shock absorber behaviour have been analysed; although many of them present differences, the only significant one was the pressure level, slightly lower in the shock absorber with high wall compliance. This is significant: lower operative pressure are related to lower mechanical stress into the component, and this should be considered during the design phase.

Despite the increased hysteresis, results of full vehicle simulations indicate that the entire system dynamic is not affected significantly, in the case of handling, primary ride and comfort. This is an important result, because it opens the doors to further investigation about this topic and to eventual practical applications.

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