

Physical Modeling and Simulation Analysis of an Advanced Automotive Racing Shock Absorber using the 1D Simulation Tool AMESim

Maryam Sadeghi Reineh
Linköping University, Automatic Control

Matteo Pelosi
Öhlins Racing AB

ABSTRACT

Shock absorbers are crucial components of a vehicle's chassis, responsible for the trade-off between stability, handling, and passenger comfort. Their role is to filter the disturbances imposed to the vehicle body, typically by passive energy dissipation through hydraulic oil. The aim of this research paper is to investigate the physical behavior of an advanced automotive racing shock absorber, known as TTR, developed by Öhlins Racing AB. This goal is achieved by developing a detailed lumped parameter numerical model of the entire TTR suspension in the 1D simulation tool, AMESim. TTR features a through-rod piston design, fully adjustable high and low speed compression and rebound adjusters, and a gas reservoir. The developed numerical model is capable of capturing the physics behind the real shock absorber damping characteristics, under both static and dynamic conditions. In particular, the model is presented in two levels of progressive physical complexity, in order to improve the numerical predictions of dynamic damping characteristics. Several physical phenomena are considered, such as the dynamics of the hydraulic volumes, the static and viscous frictions and the pressure induced elastic deformation of the solid boundaries. Model validation is discussed, based on different types of measurements for both the individual hydraulic components and the entire shock absorber model. The coupled hydraulic and mechanical modeling together with the measurement comparisons, thoroughly discussed in the paper, allows discovering the influence of each single component on the shock absorber static and dynamic performance.

CITATION: Sadeghi Reineh, M. and Pelosi, M., "Physical Modeling and Simulation Analysis of an Advanced Automotive Racing Shock Absorber using the 1D Simulation Tool AMESim," *SAE Int. J. Passeng. Cars - Mech. Syst.* 6(1):2013, doi: 10.4271/2013-01-0168.

INTRODUCTION

When driving on road, many factors, such as bumping, speed and steering, may cause relative motion and vibration between sprung (quarter body) and unsprung (wheel) mass. Conventional passive shock absorbers have the role of improving the vehicle dynamics performance by damping chassis oscillations. They typically dissipate mechanical energy, converting viscous friction into heat. The relative position and motion between vehicle body and wheels are controlled through the shock absorbers characteristics and settings, where a trade-off between driving comfort and road handling is achieved [1].

The response of a shock absorber is influenced by a variety of physical phenomena, which are usually difficult to calculate. Several authors, for this reason, performed

comprehensive measurements campaigns to understand and characterize the dynamic behavior of a shock absorber [2-3]. However, in order to be able to investigate the influence of different physical parameters on the shock absorber behavior and to accurately predict the damping response, detailed analytical models are required. Efforts in this direction have been made, such as modeling conventional shock absorbers using experimental data [4-5] and simulating damper fluid flow characteristics using computational fluid dynamics techniques [6-7]. Talbott [8] proposed a mathematical model of a mono-tube racing damper which was validated based on experimental data.

In this paper a novel AMESim model of an advanced automotive twin-tube racing shock absorber, manufactured by Öhlins Racing AB, is presented. The developed model couples and considers the mutual dynamic interaction of all

the many different hydraulic components of the damper. The various fully adjustable hydraulic elements, fundamental for the tuning of the damping behavior, are individually analyzed and modeled, to extract their specific physical characteristics. Hence, understanding and numerically capturing the real performance of each hydraulic component and of the entire shock absorber, while providing a comprehensive experimental validation of all the specific models, represents the main contribution of this work.

A depiction of the analyzed Öhlins Racing shock absorber, called TTR, together with one of its most typical racing applications, is shown in [Figure 1](#). In particular, TTR is a twin tube 4-way fully independent adjustable damper, originally developed for automotive road racing.

This research work not only allowed to increase the understanding of the physical phenomena involved in the shock absorber operation, but provides support for further product development.



Figure 1. Öhlins Racing TTR shock absorber with a typical road racing application

In fact, in this paper it is shown how the implemented mathematical model accurately replicates the static and dynamic behavior of the shock absorber.

THE ÖHLINS RACING TTR SHOCK ABSORBER

The Öhlins Racing TTR damper, shown with a cut view in [Figure 2](#), is composed of a main cylinder with through-rod piston design and a gas reservoir located on the low pressure hydraulic line, which connects the compression and rebound sides. In addition, the piston/cylinder assembly presents a twin tube configuration. The complete shock absorber assembly is equipped with a coil spring, which provides the system with a specific stiffness. In this work, the damper coil is excluded from the model. In fact, the focus of this research is on understanding and predicting the hydraulic damper dynamics, which is considered to be the most critical component in influencing the overall shock behavior.

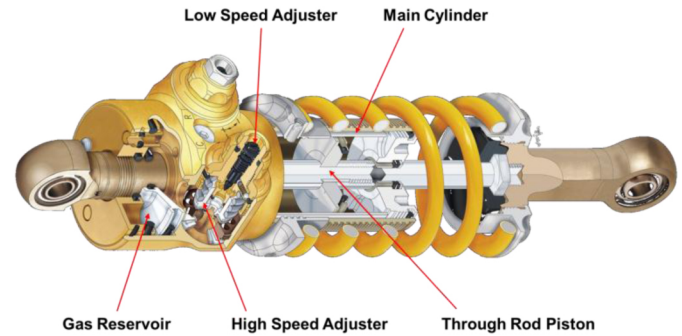


Figure 2. Öhlins Racing TTR cutaway view

Referring to [Figure 2](#), the high speed and low speed adjusters are special hydraulic valves, which can be modified in terms of flow metering characteristics by means of external accessible screws. Adjustment is done in a series of discrete numbers called *clicks*. In particular, the low speed adjuster (LSA) is a fixed orifice, while the high speed adjuster (HSA) is a special spring-loaded poppet valve. The adjusters are responsible for controlling the piston low and high speed velocity regions respectively. The adjusters are the same for the compression and rebound hydraulic circuits of the TTR damper, as shown by [Figure 3](#), where a schematic view of the shock absorber hydraulic system is depicted.

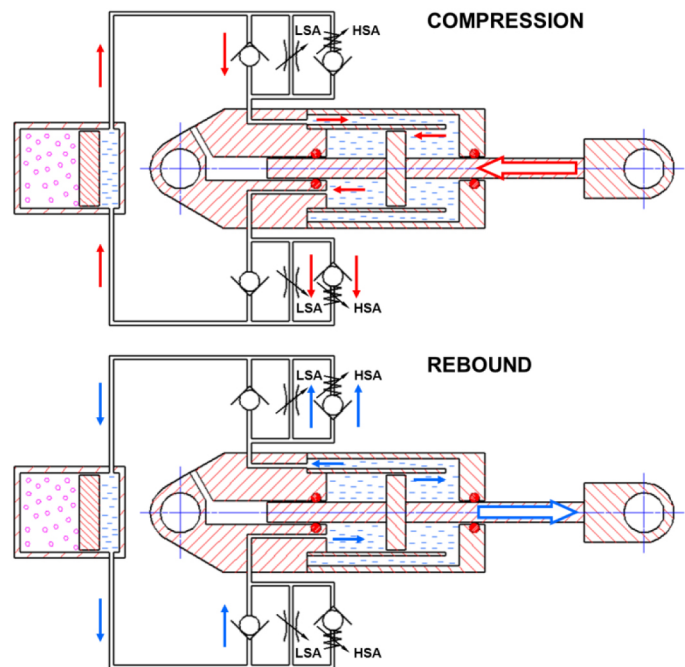


Figure 3. Öhlins racing TTR hydraulic system and cycles

The hydraulic system can generally undergo two separate cycles, according to the piston velocity direction: compression and rebound. Considering the compression cycle, following the arrows in [Figure 3](#) (top), the piston moves from right to left and pushes the flow from the cylinder compression chamber to the accumulator through the

compression side adjusters. From the low pressure rebound side the fluid flows, through a check valve and the outer tube, to the rebound chamber. During the rebound cycle, shown at the bottom of Figure 3, the hydraulic oil flows in the reversed path. As previously stated, the compression and rebound sides are identical in terms of the components which are a high speed adjuster, a low speed adjuster, and a check valve mounted in parallel. The gas reservoir sets a specific pressure level in the system.

Figure 4 schematically shows the activation of the damper components during the two different cycles. The system is fed by velocity input, which results in the generation of a damping force. As shown in Figure 4, during the compression cycle the oil flows through the high and low speed adjusters on the compression side and the check valve on the rebound side, while the rest of the valve components are active in the rebound cycle.

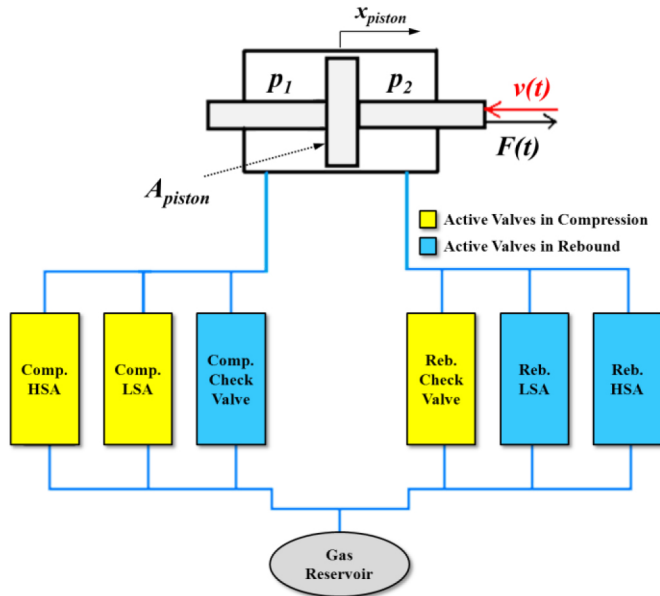


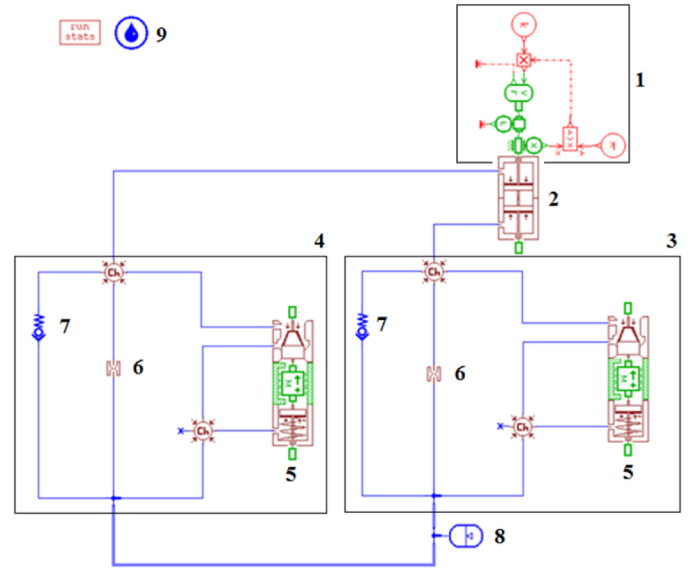
Figure 4. Active components for compression and rebound

THE AMESim MODEL

A physical model of the TTR shock absorber, which mathematically characterizes the real damper behavior, is presented in this section and shown within the AMESim environment in Figure 5.

The material presented in this paper is a summary of the work carried out in [9]. The model is compared against static and dynamic measurements, performed on the real shock absorber. This first model to be discussed includes several physical simplifications, which avoid capturing accurately the damper dynamic behavior, while accurately simulating the static performance. For these reasons, a further development of the model will be discussed, necessary in order to enhance its ability to describe the dynamic behavior of the real damper. Referring to Figure 5, the AMESim model is

composed of a number of sub-models which are implemented individually and connected properly to replicate the shock absorber hydraulic circuit and flow paths. In the following paragraphs, the main sub-models will be briefly described.



1 Input control loop; 2 Main piston/cylinder; 3 Compression side; 4 Rebound side; 5 High speed adjusters; 6 Low speed adjusters; 7 Check valves; 8 Accumulator; 9 Hydraulic oil

Figure 5. The AMESim TTR model

Main Piston/Cylinder Sub-model

Using the Hydraulic Component Design (HCD) library of AMESim, the main piston/cylinder assembly model is composed of two identical cylinder chambers. They represent a fixed body with a through rod piston design. For each of the cylinder chambers, a variable volume is considered, which is responsible for simulating the pressure transient dynamics. The main piston/cylinder sub-model determines the time derivative of pressure based on the effective bulk modulus, B_{oil} , the time dependent volume of the chamber, V_{ch} , the flow rates in and out of the chamber, Q_i , and the impact of piston motion, $\dot{x}$, as shown by Eq. 1.

$$\dot{p} = \frac{B_{oil}}{V_{ch}} \left(\sum_i Q_i + \dot{x}_{piston} \cdot A_{piston} \right) \quad (1)$$

Model parameters are tuned based on the real geometrical dimensions and stroke lengths. During piston motion, the fluid flow is distributed from the main cylinder variable chambers to the metering adjusters, in order to regulate the piston damped dynamic characteristic.

External Adjusters

The Öhlins TTR damper is equipped with four external adjusters in two groups of high and low speed. Each of the

compression and rebound sides is equipped with a low and a high speed adjuster. The adjusters can be tuned in their oil flow metering behavior by means of external accessible screws, which *click* into different positions in a discrete series of numbers. Different *clicks* setting combinations result in different damping characteristics of the shock absorber, both at low and high piston speeds and separately for compression and rebound strokes.

Low Speed Adjusters LSA

Low speed adjusters, referred also as bleed valves, are externally adjustable orifices, presenting a fixed opening diameter after a specific *click* adjustment. Hence, the metering area does not vary with the pressure difference. The low speed adjuster is mounted in parallel with the high speed adjuster; therefore as long as the piston is moving and the low speed adjuster is not fully closed, some oil will always flow through it. The AMESim LSA sub-model calculates the fluid density and kinematic viscosity at the mean orifice pressure. The sub-model has the ability to change its characteristics from laminar to turbulent flow, when passing the user specified transition value. The flow number and flow coefficient, C_q , are calculated based on the fluid Reynolds number and are used in the orifice flow equation, presented by Eq. 2.

$$q = C_q A_{LSA} \sqrt{\frac{2|\Delta p|}{\rho}} \text{sign}(\Delta p) \quad (2)$$

High Speed Adjusters HSA

High speed adjusters, as is shown in Figure 6, are conical poppet valves, pushed against their seats by pre-loaded coil springs.

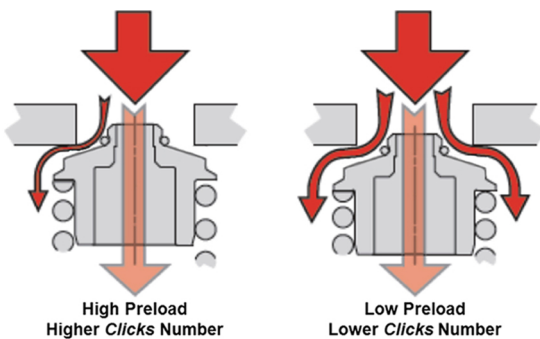


Figure 6. Poppet valve opening characteristics

The amount of spring pre-load determines the pressure difference across the main piston necessary to open the poppet and let the HSA regulate the shock absorber damping characteristic. The HSA springs pre-load is externally adjustable in a series of discrete *clicks* through special screws. The HSA AMESim model is composed of a conical poppet, sketched in Figure 7, a piston with spring, and a mass with friction.

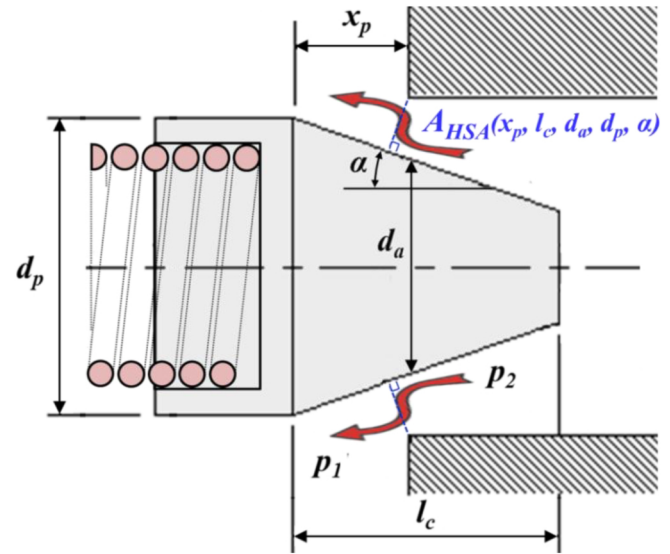


Figure 7. HSA conical poppet geometrical model

The most critical issue in modeling the HSA is the conical poppet, which dictates the flow behavior and consequently the damping characteristics. As shown in Figure 7, different flow efflux areas are defined, depending on the position of the poppet with respect to the seat. At each of the poppet positions, the active diameter, d_a , and consequently the flow area are calculated using the perpendicular distance from the poppet to the valve seat.

Other Hydraulic Components

The remaining sub-models are the check valves and the gas reservoir. The check valves are responsible for separating the compression and rebound sides. In this preliminary modeling phase, it is simulated using the basic AMESim hydraulic library, as a simple spring loaded valve which considers no dynamics. The check valve opens if the pressure difference over it becomes larger than the cracking pressure, set by the spring pre-load. Furthermore, the shock absorber gas reservoir, responsible for setting the system pressure level, is modeled as a basic accumulator. The through-rod design of the TTR shock absorber helps to decrease the effect of the accumulator properties on the damping behavior.

Input Control Loop

The main input to the damper model is velocity applied to the piston rod, and the output is a resistive force generated on the rod by the damper. A numerical loop is necessary in order to synchronize the input velocity signal with the piston simulated displacement. The input velocity defines the type of test cycle underwent by the shock absorber, described in detail the following section. The measured output damping force as a function of damper velocity represents the main output of the test. Specific measurements from such cycles are used to validate the developed AMESim numerical model.