

Double Hydraulic Stop (DHS) Suspension

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1 Introduction

From a physical point of view, vehicle suspensions are characterized by their stiffness and damping. Since the beginning of the automobile industry, these two parameters have been adapted to provide the best driving experience according to the market standards on each moment. In general, their optimal design is defined as a compromise between ride comfort and handling. As they are involved in the car performance not only for vertical movement, but also for roll, yaw and pitch behavior, the best setting changes from one driving condition to another.

Many developments have been carried out to find and improved compromise between stiffness and damping such as air suspension, hydropneumatic suspension or semi-active dampers. All these technologies are focused on improving the standard passive suspension by better adapting suspension stiffness or/and damping to the vehicle instantaneous demands. To do so, they use a common architecture where a certain combination of sensors, ECUs and actuators is essential, adding cost and complexity to vehicle suspension. As a result, these systems are frequently being relegated to the higher vehicle trim levels, or even disappearing from the market.

In the last years, KYB has faced this subject from a different perspective. KYB's proposal is an enhanced passive suspension that respects the simplicity and effectiveness of standard suspension, boosting its performance at an affordable cost.

2 Double Hydraulic Stop suspension concept

The Double Hydraulic Stop (DHS) suspension is based on providing the right blend of stiffness and damping throughout the full suspension travel.

As shown in Fig. 1, the standard passive suspension is composed of elastic and damping components. The suspension spring, the stabilizer bar, the bumper, the rebound stop and the rubber bushings could be classified as elastic parts. Apart from the limited rubber viscous damping, the shock absorber is the only damping component in car suspension. Whenever the vehicle rides, the kinetic energy induced by the road or driver actions is stored by the elastic components and dissipated, mainly, by the shock absorber.

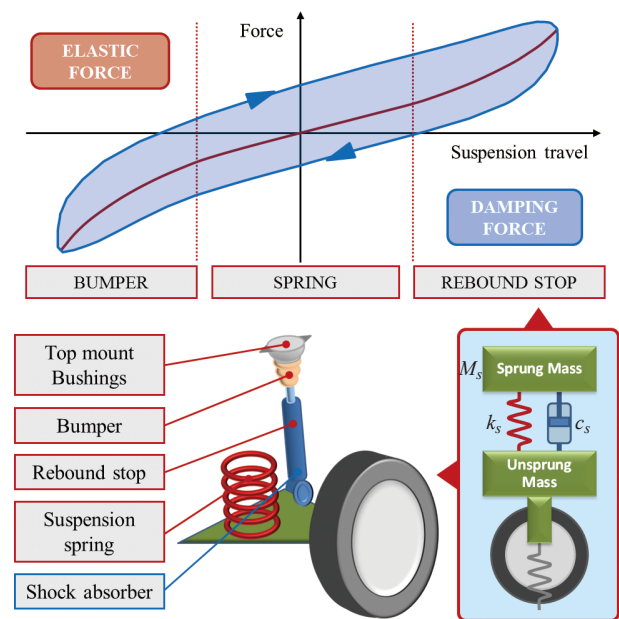


Fig. 1 Quarter-car suspension model (lumped parameters). Elastic and damping components in a standard passive suspension and their function

The spring is the main elastic component in suspension, being responsible for supporting the sprung mass (vehicle body, frame, passengers...) and defining the ride frequency as a relation between its stiffness (k_s in the quarter-car model, and the slope of red line in Fig. 2) and the sprung mass (m_s in the quarter-car model). The ride frequency is a decisive parameter that establishes the frequency of the sprung mass vertical movements, that is directly related to the handling/comfort compromise.

The shock absorber, as it is the main energy dissipating element, will control the sprung mass oscillations decay after each disturbance. The right amount of damping (C_s in the quarter-car model) to be added is a function of the sprung weight, the spring rate and the desired performance for each suspension velocity range. A dimensionless parameter, named damping ratio, is defined to describe the oscillations decay pattern. As shown in Fig. 2, a damping ratio of 1 means that the suspension is critically damped and its response will be the fastest without overshoot. Values close to this level are chosen for low velocity oscillations, which are associated with handling. Low damping ratios will provide a fast and underdamped response, well adapted to provide comfort and usually chosen for medium and high suspension velocities.

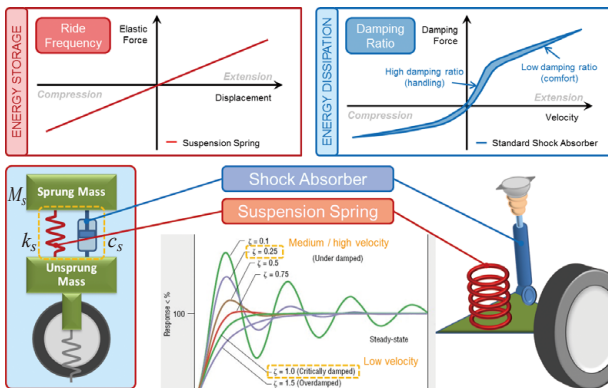


Fig. 2 Roll of suspension spring and shock absorber in damping ratio definition

The suspension is now perfectly balanced whenever it works around its reference position. However, neither the spring nor the shock absorber are capable to adapt their response in the surroundings of the suspension stroke ends, where additional effort is required to avoid

impacts and noise.

The standard solution for this issue is to incorporate two new elastic components, the rebound stop for extension and the bumper for compression. They will reduce suspension travel velocity as it reaches its stroke end, but the energy in excess will be fully stored and subsequently released leading to discomfort and too many oscillations before settling. In addition, as these components are not velocity sensitive, they cannot guarantee an optimal performance at high suspension travel speeds, still allowing undesired noise and acceleration peaks.

In Fig. 3, this is analyzed in terms of damping ratio. The spring elastic curve (red graph) has been reinforced in the surroundings of each stroke end. However, the response type of the shock absorber subjected to a sinusoidal oscillation (blue graph) shows a decrease in damping capability, linked to travel speed reduction in the stroke ends surroundings. The stiffness increment along with damping decline, conducts to an undesired damping ratio decrease that will degrade suspension performance.

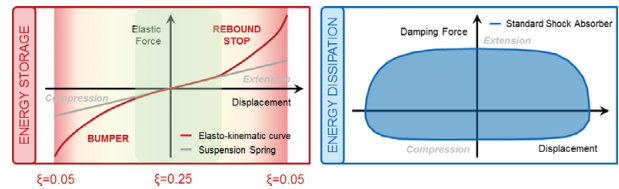


Fig. 3 Damping ratio change in the surroundings of the stroke ends after bumper and rebound stop incorporation

The damping ratio approach is very useful to understand DHS philosophy. DHS function has been added to a standard damping cycle in Fig. 4 (blue graph). The DHS shock absorber includes two subsystems, one focused on smoothening the extension stroke ends (Hydraulic Rebound Stop, HRS) and the other acting for compression stroke ends (Hydraulic Compression Stop, HCS). Both of them are able to progressively reinforce damping capability as the stroke ends are reached, accommodating their response to the movement velocity. The elastic curve (red graph) has also been modified in order to lower the bumper and rebound stop contributions. As a result, the desired damping ratio is kept along the entire

stroke length, minimizing suspension oscillations with an improved ride comfort. As DHS is mainly based on damping, it is fully capable to manage high velocity stroke ends.

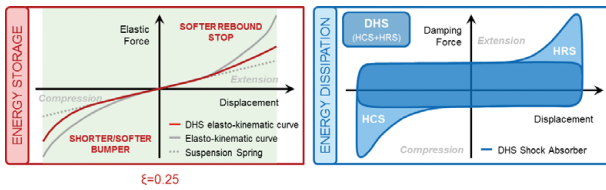


Fig. 4 Damping ratio improvement after including DHS concept and the adjustment of bumper and rebound stop

3 DHS architecture: HCS & HRS

As mentioned before, DHS is integrated by the Hydraulic Compression Stop (HCS), a first subsystem devoted to control compression stroke ends, and the Hydraulic Rebound Stop (HRS), a second subsystem dedicated to improve extension stroke ends. Both are passive systems that are installed inside the shock absorber body, as displayed in Fig. 5. A standard shock absorber equipped with DHS will generate the force-displacement curve shown below, characterized by an additional energy dissipation capability that builds progressively as both stroke ends are reached. HCS and HRS will be analyzed separately in the following paragraphs.

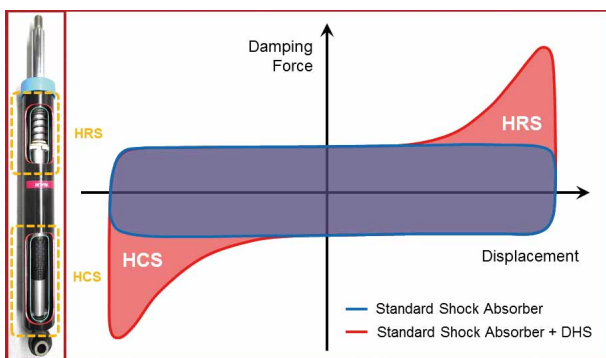


Fig. 5 HCS and HRS installation in the shock absorber and sample of function

4 DHS subsystems: HCS description

HCS is a damping-based fully dissipative device that is intended to work together with a simplified bumper version. It offers a tunable progressivity with suspension stroke to provide a dissipative

bumper-like function. The simplified bumper will still be responsible for managing the last millimeters of compression stroke, to avoid the risk of a damping lack when the stroke end is reached slowly. HCS has been conceived to work in parallel with the main shock absorber components and flows, without altering them and respecting the main damping law.

As shown in Fig. 6, HCS is partially installed on the piston rod and mainly placed in the bottom of the inner tube. Once the shock absorber is compressed enough to overlap the HCS plunger with the HCS tube, the shock absorber compression chamber is divided in two portions. The outer one, delimited by the plunger, the HCS tube, the shock absorber inner tube and the HCS base valve, is named HCS chamber.

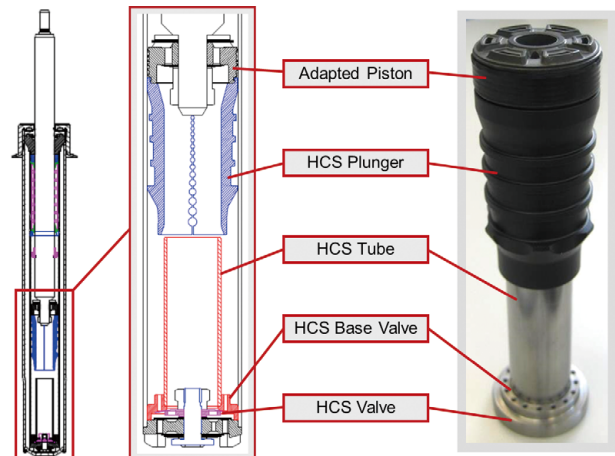


Fig. 6 HCS: installation, construction and components description

As the shock absorber is further compressed, the pressure in HCS chamber rises. The trapped oil has two possible paths to reach the original compression chamber and join the main shock absorber's oil flow: a group of orifices practiced in the plunger and through the HCS valve (see Fig. 7), which is preloaded to operate as a pressure relief valve. In consequence, while the pressure in HCS chamber doesn't exceed the relief pressure, the oil will be forced to flow through the plunger orifices. These passages are gradually closed by the HCS tube as the shock absorber is compressed, bringing an additional pressure increment. The HCS pressure raise is limited to the preset relief pressure of HCS valve, which will open to allow the oil quitting the HCS chamber

easily. This condition is normally reached at the end of the compression stroke, allowing the plunger orifices to control the HCS force increase with stroke, while the HCS valve is responsible for regulating the maximum force at each compression velocity.

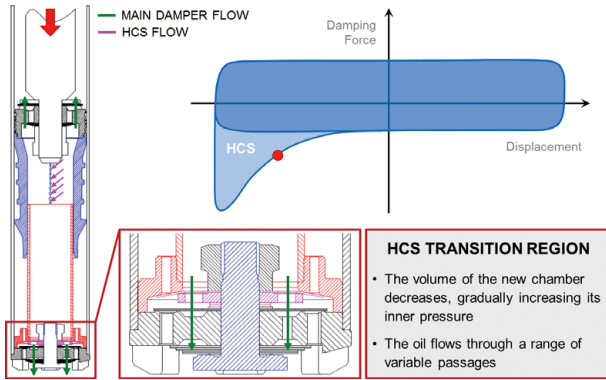


Fig. 7 HCS working principle and flow distribution

The working principle described above has the advantage of limiting the maximum HCS force even for the high compression velocities registered in suspension during normal driving. Moreover, the high preload/stiffness ratio used for HCS valve provides high damping force at low velocity while keeps it moderate at high velocity.

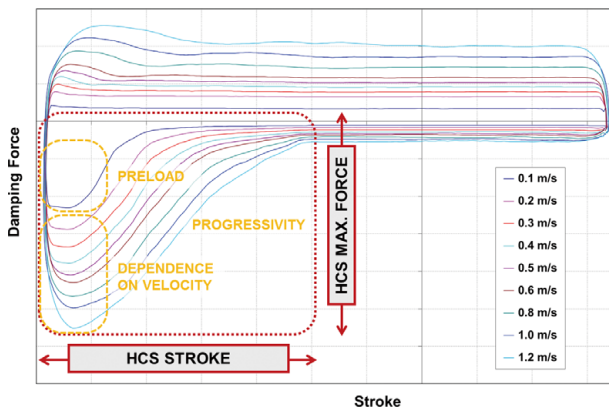


Fig. 8 HCS function: tunability options

As summarized in Fig. 8, HCS is a highly tunable technology. Apart from system stroke and maximum force, HCS progressivity, preload and dependence on velocity can be tuned. Progressivity is defined by the chosen sequence of plunger orifices. HCS preload and force gain with velocity increase are adjusted with the assembly deformation of HCS valve and its stiffness respectively.

5 DHS subsystems: HRS description

HRS is a combination of elastic and hydraulic device focused on replacing the conventional mechanic rebound stop. The HRS elastic content guarantees the function at low extension velocities, while the hydraulic one reinforces its performance at higher velocities, by making the system sensitive to movement speed. Short stroke versions are focused on noise and acceleration peaks reduction, while long versions are also suitable for vehicle dynamics improvement. In that case, the dissipative content of HRS is a great tool to improve roll and pitch control. HRS has been conceived to work in parallel with the main shock absorber components and flows, without interfering with them and respecting the main damping law.

HRS is essentially implanted in the upper area of an inner tube that has been radially expanded with a conical shape (see Fig. 9), comprising a rubber stop, a spring with plastic washers and an open segment. The system is completed with a metallic washer assembled on the piston rod. When the shock absorber stroke is enough to make the rebound stop washer contact the segment, the shock absorber rebound chamber is divided in two sections. The upper one, that is defined by the guide, the rod, the deformed portion of the inner tube, the segment and the rebound washer, is named HRS chamber.

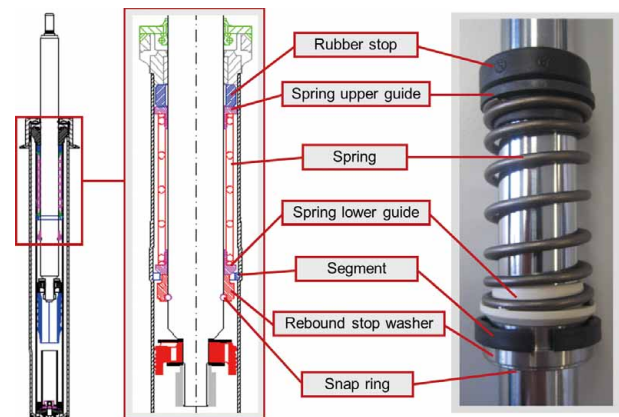


Fig. 9 HRS: installation, construction and components description

As the shock absorber is further extended, the oil in HRS chamber is compressed and its pressure rises. The open segment counts with two kinds of

passages to regulate this pressure build-up: the gap between ends constitutes the main control path, while a number of reliefs are responsible for the force increment regulation.

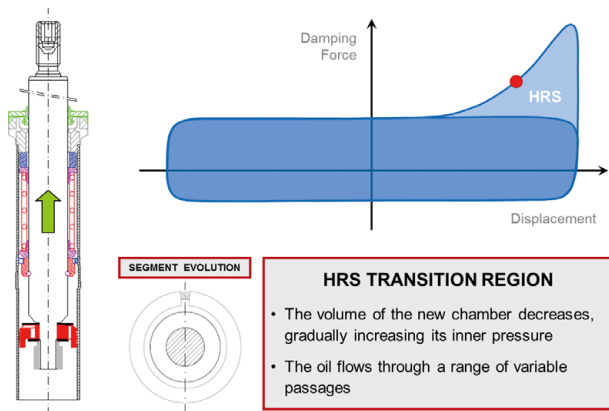


Fig. 10 HRS working principle

At the HRS entry point, the open segment rests in the maximum diameter of the inner tube deformation. At this position, the separation between both segment ends is maximum and the reliefs are fully open, allowing the oil to escape easily from the HRS chamber. As shown in Fig. 10, the more the segment is dragged through the conical shape of the tube expansion, the smaller becomes the gap between segment ends and the reliefs passage, resulting in an increased damping force. Once the stroke end is reached, the spring is blocked and a rubber stop deforms to filter any eventual acceleration peak transferred to the chassis.

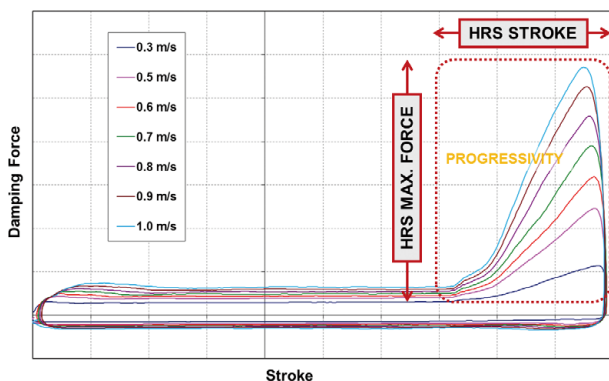


Fig. 11 HRS function: tunability options

Due to the more deterministic character of the suspension extension movements compared to compression ones, HRS needs not be as tunable as HCS. Compression movements are induced by road irregularities working against a high inertia

car body, thus being able to impose really high compression velocities. On the contrary, extension strokes are regulated by the elastic energy released to the low inertia unsprung mass by suspension spring, deploying predictable travels at no so high velocity. In such a scenario, it is not necessary to use a pressure relief device to avoid excessive load at high velocity. As shown in Fig. 11, adjusting the stroke, the maximum force and, eventually, the damping force build-up is enough.

6 Conclusion

A new passive suspension concept has been developed. The treatment of suspension stroke ends provided by DHS brings a new comfort standard to automobile industry. It is an affordable passive solution easy to implement in no matters which suspension architecture, and highly tunable to match customer expectations. In fact, this is a key factor to explain the system success, because DHS allows to car makers offering a high class suspension starting from the most basic trim level of a vehicle.

A second key point is the system versatility: DHS can be configured to create an outstanding comfortable vehicle, or to achieve a better dynamic performance by combining a good, well-tuned passive shock absorber with DHS to, for instance, compete with adaptive suspensions.

Last but not least, DHS is easily perceived by anyone who drives the vehicle, due to the granted smoothness and the absence of rebounds when driving through obstacles and bad roads.

As a result, DHS is receiving a very good acceptance from the market both, in sales and with positive reviews from the specialized press.

7 Further development

DHS, as a passive hydro-mechanical device, is also well positioned to contribute to improve semi-active suspensions. Properly managing the suspension stroke ends demands shock absorbers adapting their response in few milliseconds. This is a hard task for an electronic suspension, because not only a fast response actuator is required, but also the sensors and control strategy

have to make the right decision within such a short time interval. On the contrary, it is an easy task for a passive system, which instantaneously acts in a predictable and repeatable way whenever a certain input is applied. Merging the great potential of semi-active suspensions with the fast passive response of DHS would boost the system performance.

8 Acknowledgements

I would like to express my deep gratitude and sincere appreciation to all my colleagues, engineers and technicians, who have contributed decisively to the final success of this challenging development.

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