Technology Introduction

Externally-Mounted Shock Absorber with Adjustable Solenoid Damping Force Development of New Type of Solenoid and improvement of a Comfortable Ride & Quietness

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1 Introduction

Since their introduction around 2000, the use of semi-active suspensions in motor vehicles has been increasing every year. The number of vehicles with these suspensions is expected to rise in the future (Fig. 1).

A semi-active suspension is a suspension system that controls the damping force of the vehicle in real time in response to changing input from the road surface. It is intended to approximately implement the active suspension [Note 1)] by means of damping force adjustable shock absorbers (hereinafter "adjustable SAs").

Note 1) A suspension system with a power source that can apply a load in either direction of vibration excitation or damping depending on the road surface condition.

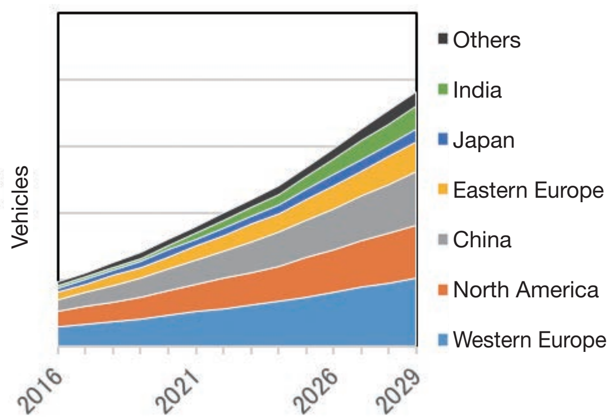

Fig. 1 Projected number of vehicles equipped with semi-active suspensions

There are several types of adjustable SAs as shown in Fig. 2, where they are classified by damping force adjusting system, and Fig. 3, where they are classified by damping force adjusting valve position.

For the damping force adjusting system, the solenoid type is normally used today. For the damping force adjusting valve position, it is common to install the valve outside the shock absorber (externally-mounted type).

KYB uses this popular adjustable SA with a solenoid control valve (hereinafter "SOL valve") mounted externally to the shock absorber. The company has mass-produced these adjustable SAs with externally-mounted SOL since the end of 2016. (Photo 1)

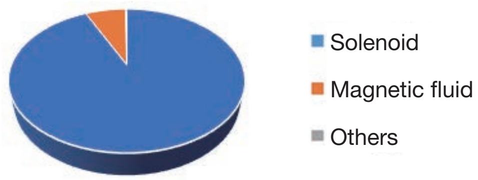

Fig. 2 Share of damping force adjusting system (FY2019)

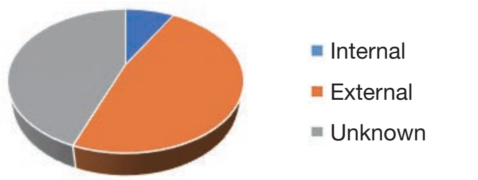

Fig. 3 Share of damping force adjusting valve position (FY2019)

Photo 1 KYB adjustable SA with externally-mounted solenoid

KYB further improved the riding comfort and quietness of the adjustable SA with externally-mounted solenoid to satisfy market demand and started its mass production at the end of 2020. This paper introduces the technology.

2 Riding Comfort

This section explains which property of the adjustable SA affects the riding comfort of the motor vehicle and the aim of the improvement.

2.1 Riding Comfort of Vehicles and Damping Force of Adjustable SA

Fig. 4 roughly illustrates the damping force of the adjustable SA. As shown in the figure, what most affects the riding comfort of the vehicle is the damping force generated in soft mode [2].

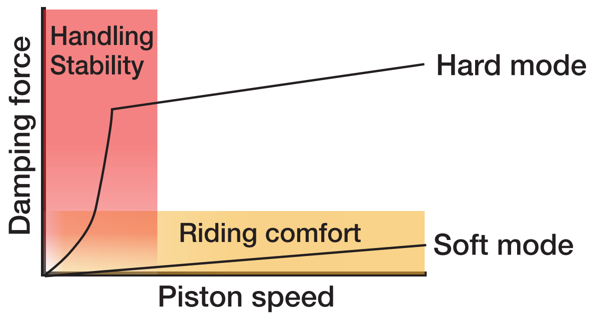

Fig. 4 Damping force of adjustable SA

The damping force in soft mode not only affects the ride comfort but also plays the role of ensuring minimum adhesion to the road.

From the point of view of ride comfort, the lower the damping force in soft mode is, the easier it is to alleviate or block the input from the road surface.

From the point of view of adhesion, however, some degree of damping force is needed to yield an appropriate level of damping coefficient. Thus, the damping force in soft mode involves two mutually contradictory demands [3].

2.2 Aim of Improvement of Soft-mode Damping Force

Fig. 5 shows the relationship between piston speed and damping force. As shown in the figure, the condition for a constant damping coefficient can be plotted as a dotted straight line with a constant slope against the piston speed.

To improve the riding comfort while maintaining the adhesion, we improved the SOL valve in such a manner that a lower damping force can be produced only in the range of lower piston speed, as plotted by the red line in Fig. 5. This improved SA is aimed at blocking or alleviating small inputs from the road surface for better ride comfort while ensuring the required performance for large inputs that may impede the adhesion.

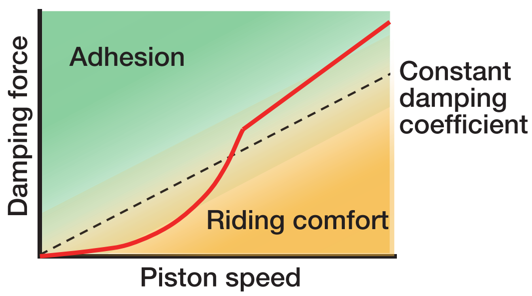

Fig. 5 Aim of improved soft-mode damping force and damping coefficient

3 Quietness

Among abnormal noises issued by a motor vehicle, the one pertaining to its shock absorbers is rattle. When you drive a car on a somewhat rough, simply-paved road at a low speed of 10 to 30 km/hr., you may hear internal rattle at a frequency of several hundred hertz.

The sound transfer system is shown in Fig. 6. When the shock absorber changes the direction of stroke, a load change occurs, which may excite the vibration of the piston rod. The vibration is transferred to the vehicle body via the body mount (insulator), producing resonance to emit the rattling noise [4].

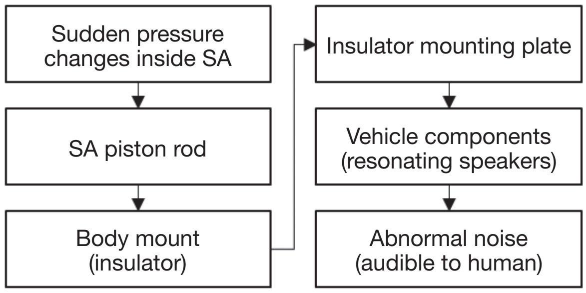

Fig. 6 Rattling noise transfer system

In many cases, the sudden load change in the shock absorber to which the rattling noise is attributable occurs during the valve operation (opening). This is because the pressure characteristics dramatically change before and after the valve operation. One of the effective measures to reduce the change is to enlarge the orifice installed in parallel with the valve.

4 Improvement of SOL Valve

This section provides an overview and description of the improvement of the SOL valve that is used to adjust the damping force of the adjustable SA with externally-mounted solenoid and also explains what necessitated the development of the new solenoid.

4.1 Overview and Improvement

The adjustable SA with externally-mounted solenoid has a triple-tube structure through which the hydraulic fluid flows into the SOL valve during both the expansion and contraction strokes of the shock absorber. The SOL valve uses a pilot-type electromagnetic proportional relief valve to regulate the hydraulic pressure with the solenoid thrust according to the magnitude of the control current. This eventually adjusts the damping force of the shock absorber.

Fig. 7 shows a simple model of the SOL valve, and Fig. 8 a hydraulic circuit diagram of the SOL valve.

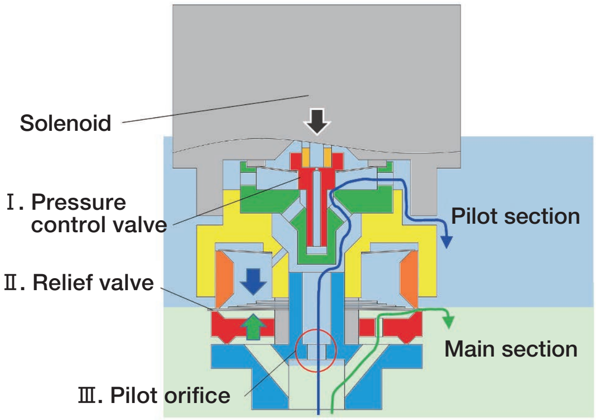

Fig. 7 Simple model of SOL valve

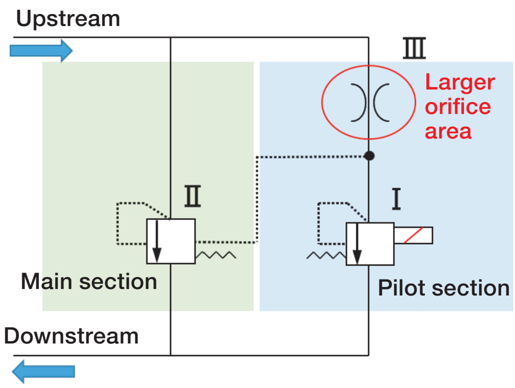

Fig. 8 Hydraulic circuit diagram of SOL valve

The following describes how the SOL valve operates:

① Receiving the solenoid thrust against the flow in the pilot section, the pressure control valve I controls the pilot pressure.

② With the pilot pressure, the relief valve II is applied with a load in the direction of closing.

③ As the pilot flow increases, the pilot orifice III has a higher differential pressure to raise the pressure in the main section.

④ As the load generated by the pressure in the main section increases, the relief valve II is opened.

The damping force in the range of low piston speed in soft mode that should be reduced for better ride comfort is governed by the differential pressure generated in the pilot section. Then, the area of the orifice in the pilot section has been increased for improvement purpose, resulting in a lower damping force in the low piston speed range of the adjustable SA.

The use of the larger orifice has also helped reduce the sudden change of the pressure characteristics before and after the valve opening points in the main section, as shown in Fig. 9. This prevents the shock absorber from experiencing the sudden load change, contributing to lower rattling noise.

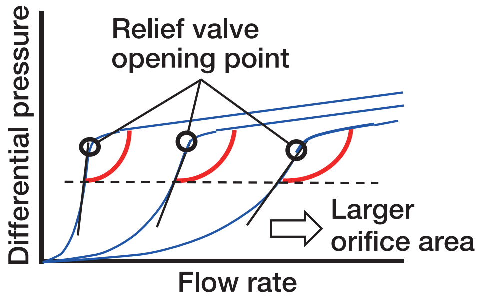

Fig. 9 Orifice area and pressure change

4.2 SOL Valve Improvement Challenges

The use of the larger orifice in the pilot section, in turn, increases the pilot flow against the piston speed, as shown in Fig. 10. For the conventional design, the SOL valve has permissible limits of pilot flow. If the limits are exceeded, the system will unintentionally enter the fail-safe mode Note 2), causing a faulty condition. In case the system unintentionally moves into the fail-safe mode during driving, the damping force will suddenly jump to worsen the ride comfort.

Note 2) A mode used to generate some degree of damping force for vehicle safety even if the electric current flowing into the adjustable SA is interrupted.

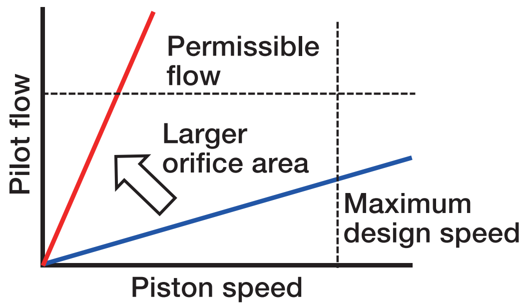

Fig. 10 Problem with conventional design

This problem occurs because the conventional design depends on the pilot flow in entering the fail-safe mode. To resolve the problem without changing the structure, the entire size of the SOL valve needed to be substantially increased. However, such a larger SOL valve cannot be mounted in place on the vehicle.

It was thus difficult to enlarge the pilot orifice with the conventional design unchanged. It was then decided to invent a new SOL valve design with which the system can enter the fail-safe mode only depending on the current, in order to develop a new solenoid design that can generate a thrust force even during a failure (0 A).

5 Development of New Solenoid

KYB had Takako Industries, INC. develop a new solenoid to solve the problem with the KYB adjustable SA. The appearance of the new solenoid is shown in Photo 2.

Photo 2 Appearance of new solenoid

5.1 Design of Solenoid

A spring is integrated in the solenoid to ensure that a thrust force is generated even during failure (0A). A double-plunger (hereinafter "DP") solenoid was invented, which consists of Plunger A that generates a proportional thrust force in energized state and Plunger B that cancels the thrust force of the spring in energized state. Fig.11 shows the behavior of DP solenoid in non-energized state, and Fig. 12 shows the behavior of DP solenoid in energized state.

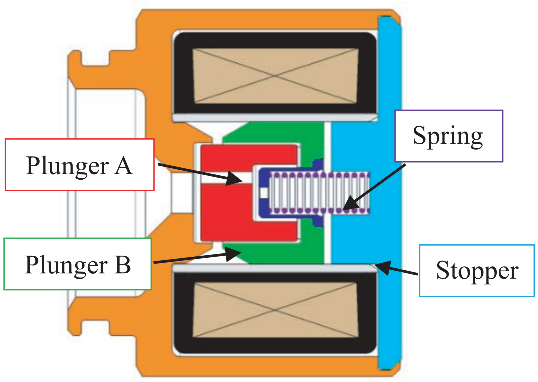

Fig. 11 Behavior of DP solenoid (non-energized state)

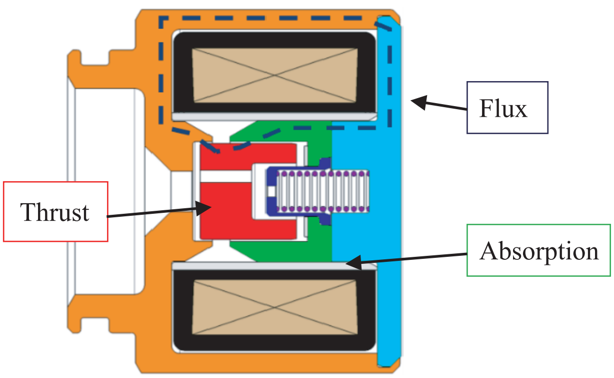

Fig. 12 Behavior of DP solenoid (energized state)

5.2 Operation of DP Solenoid

The feature of DP solenoid is that Plunger A has the thrust force characteristics of a proportional solenoid and Plunger B has the thrust force characteristics of an ON/OFF solenoid.

The thrust force characteristics of each plunger are shown in Fig.13 and Fig.14.

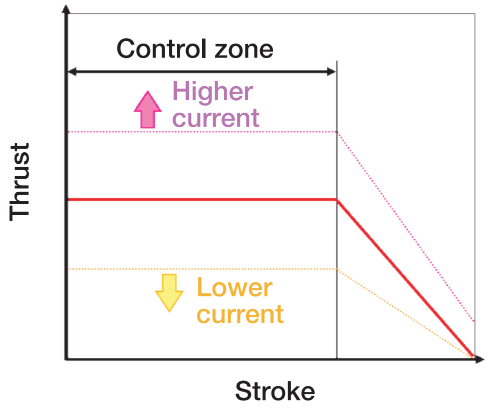

Fig. 13 Conceptual image of proportional solenoid thrust characteristics

A proportional solenoid has the thrust force characteristics that thrust force proportional to the amount of the control current can be achieved, regardless of the plunger's stroke position within the control zone.

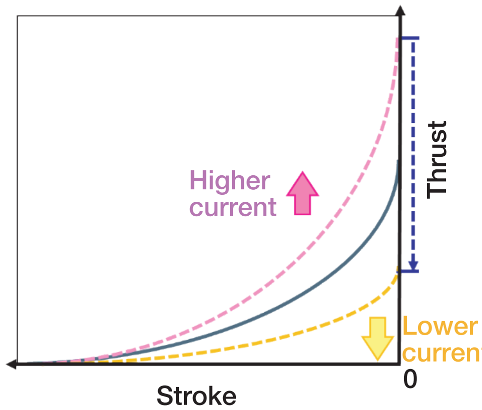

Fig. 14 Conceptual image of On/Off solenoid thrust characteristics

On the other hand, an ON/Off solenoid has the thrust force characteristics that high thrust force can be achieved at the end position (Stroke 0mm) even if the current is reduced.

The operation of DP is described in the following texts. Fig.15, Current-thrust characteristics diagram, shows conceptual image of operation.

① The thrust force is generated by the spring load in non-energized state (0A).
(This determines the damping force in the fail-safe mode.)

② Plunger B moves toward and connects to the stopper within the control current range and cancels the spring load. (The fail-safe mode is cancelled.)

③ Plunger A is free from the spring load so that it generates the thrust force according to the control current. (This determines the damping force during vehicle driving.)

④ Plunger B is released from the stopper and comes to the initial position when the current is lower than the control current range, or in non-energized state, and the spring load works.
(Back to the fail-safe mode)

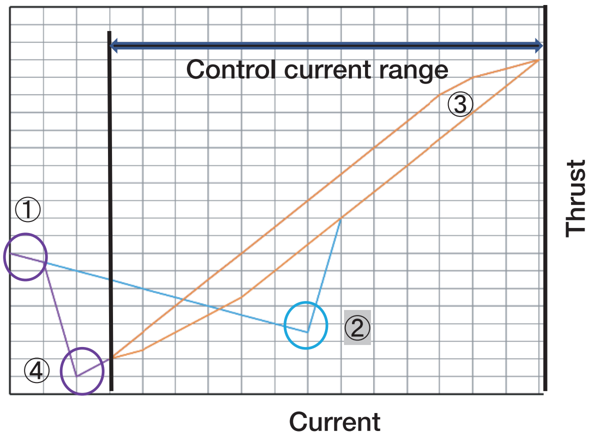

Fig. 15 Current-thrust characteristics diagram (conceptual image of operation)

With its On/Off solenoid thrust characteristics, DP solenoid can keep cancelling the spring load even with low current as long as it is within the control current range.

5.3 Feasibility of DP solenoid

It was necessary to realize both Plunger A's proportional characteristics and the thrust force at the end position of Plunger B within the size requirement (up to the maximum mountable size).

This new solenoid has a special structure in which a single coil is used to have the two plungers to generate the thrust force. We devised the method of the magnetic analysis individually on each plunger and examined the thrust force. Fig.16 shows the conceptual image of the magnetic analysis model. The analysis revealed that trade-off relationship between the proportional characteristics of Plunger A and the thrust force at the end position of Plunger B. We faced a challenge of the proportional characteristics of Plunger A in the initial prototype stage.

We examined the geometry for improvement and tried out with the prototypes. We repeated the analysis using the result of the prototype examination and finally succeeded in determining the geometry that improves the proportional characteristics of Plunger A and the optimal balance of the components.

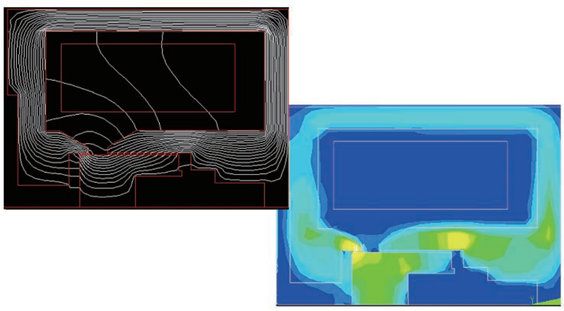

Fig. 16 Conceptual image of magnetic analysis model

5.4 Stable operation

This design indicated that if Plunger B comes off from the end position within the control current range, DP solenoid would lose the necessary function as the proportional solenoid. Therefore we studied a method to stabilize the connection force of Plunger B so that Plunger B does not come off within the control current range. The study revealed that the connection force of Plunger B becomes lower in case the passage of the magnetic flux between the components is disrupted. We considered it effective to make the solenoid stroke shorter to solve this problem.

However, the solenoid stroke also affects the performance of the shock absorber. Therefore we determined the boundary which satisfies the performance of both the solenoid and the shock absorber.

5.5 Reduction of Operation Noise

There is operation noise specific to this design. The "clink" sound occurs when Plunger B contacts the stopper. When Plunger B approaches the stopper, the thrust force becomes higher and generates sound by collision. The initial prototype which was actually mounted on the vehicle also had this sound issue.

To control the collision speed, we introduced the damping orifice function that utilizes the hydraulic fluid between Plunger B and the stopper. Fig.17 shows an enlarged view of the damping orifice section.

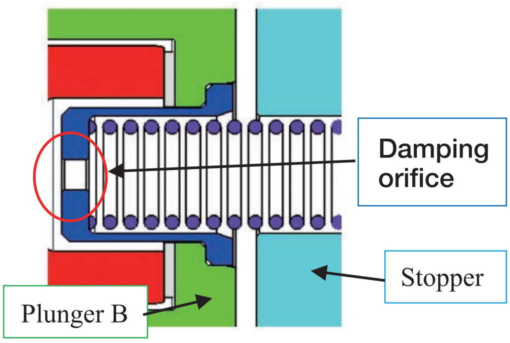

Fig. 17 Enlarged view

We checked and determined the orifice diameter that would not affect the performance of the shock absorber.

6 Current Applications

The externally-mounted shock absorber with adjustable solenoid damping force introduced in this paper has been used in the LEXUS LS [Note 3)], which was put on the market in December 2020, of Toyota Motor Corporation, and is now highly evaluated.

Other development efforts for the product to be used in several other vehicles are under way, with an aim to expand both applications and production.

Note 3) LEXUS LS is a trademark owned by Toyota Motor Corporation.

7 In Closing

We have successfully developed an externally-mounted shock absorber with adjustable solenoid damping force for higher ride quality and superior quietness to meet market needs. We will continue to improve the product to adapt to further needs.

Finally, we would like to take this opportunity to sincerely thank all those concerned who gave us guidance and cooperation for this development.

References

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