Product Introduction

Development of Externally-Mounted Shock Absorber with Adjustable Solenoid Damping Force

KAMAKURA Ryosuke, FURUTA Yusuke, MORI Toshihiro, TOMITA Kohei

1 Introduction

The automotive industry has manufactured more and more vehicles equipped with semi-active suspension (refer to Glossary "Semi-active Suspension" on p.31) since 2000 to achieve compatibility between handling stability and ride comfort. The number of these vehicles is expected to rise in the future (Fig. 1).

Automotive adjustable shock absorbers (hereinafter adjustable SA") a shock absorber with a proportional solenoid valve, that can seamlessly control the damping force in response to the control current with high switching response (Fig. 2) in the mainstream of automotive adjustable shock absorbers.

Vehicles equipped with this damping force adjustable SA are used not only in segment C, but also even in segment B (Fig. 3).

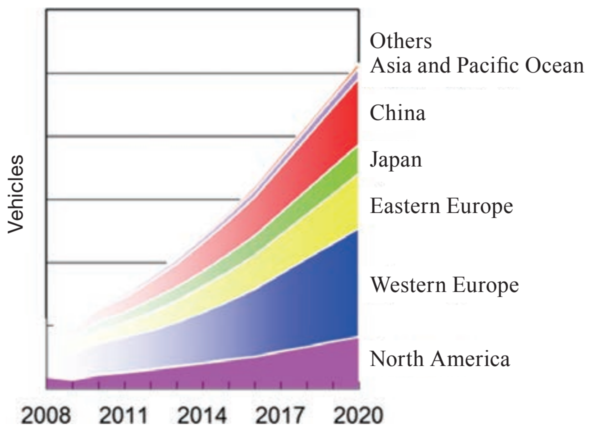

Fig. 1 Projected number of vehicles equipped with semi-active suspension

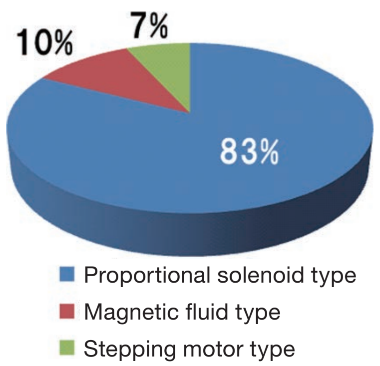

Fig. 2 Damping force adjusting systems (FY2016)

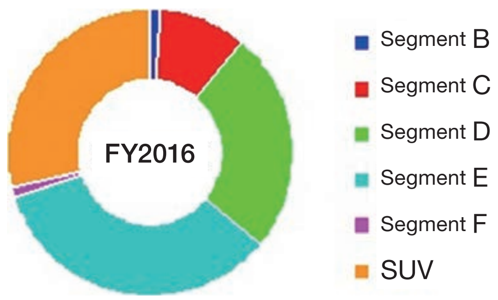

Fig. 3 Vehicles equipped with damping force adjustable SA by segment

There are two types of solenoid damping force adjustable SA. One is "internal type" with a solenoid valve installed in a shock absorber cylinder, and the other is "external type" with a solenoid valve on shock absorber cylinder. "External type" that has is in the majority of adjustable SA.

KYB has conducted mass production of adjustable SA since late 2016. This report introduces the development of adjustable SA with external solenoid (hereinafter "adjustable SA with external SOL").

2 Product Overview

2.1 Appearance

Fig. 4 shows the appearance of adjustable SA with external SOL.

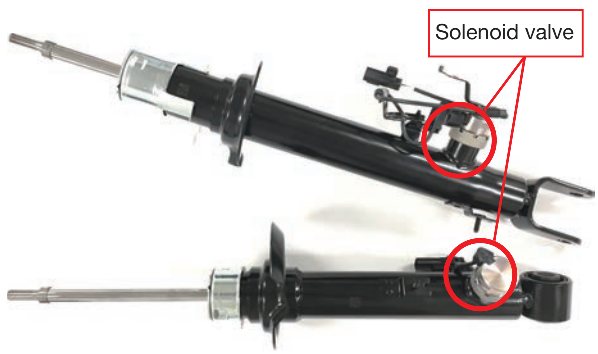

Fig. 4 Appearance of damping force adjustable SA with external SOL

2.2 Specifications

Table 1 shows the specifications of adjustable SA with external SOL.

Table 1 Specifications of adjustable SA with external SOL

Basic structure	Triple tube uniflow
Control method	Pressure control
Valve size (maximum outer diameter x height)	maximum ϕ 39 x 53 In the world smallest size for superior-vehicle mountability
Electric current	Low current: SOFT High current: HARD
Switching response	Faster than KYB's existing product (stepping motor type) by 8 times or more SOFT ⇔ HARD
At fail-safe Damping force	Can be set equivalent to HARD damping force

2.3 Target of Damping Force Characteristics

Semi-active suspension can realize both handling stability and ride comfort at a high level by widening variable range of damping force (low for SOFT damping force, high for HARD damping force) and achieving fast switching response. The damping force adjustable SA with external SOL is also designed with the aim of achieving a wide damping force adjustable range and higher switching responsivity while implementing the world's smallest valve body. Fig. 5 illustrates the target damping force characteristics.

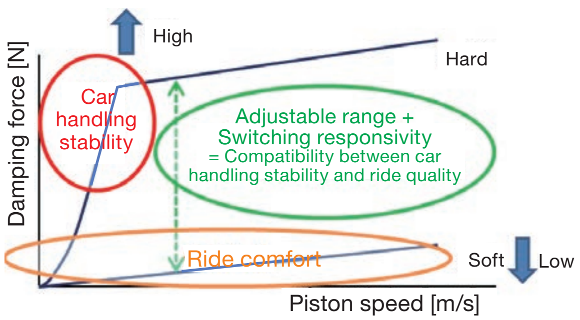

Fig. 5 Target of damping force characteristics

3 Development of Adjustable SA with External SOL

3.1 Triple Tube Configuration

To guide hydraulic oil into solenoid control valve (hereinafter "SOL valve") on a shock absorber cylinder, the development team selected a triple tube configuration conposed of a cylinder, middle pipe and outer shell. The oil flows in the shock absorber only in a single direction (uniflow) to allow the single SOL valve to adjust the damping force during both expansion and compression strokes. Fig. 6 shows the triple-tube uniflow configuration and flow of the hydraulic oil.

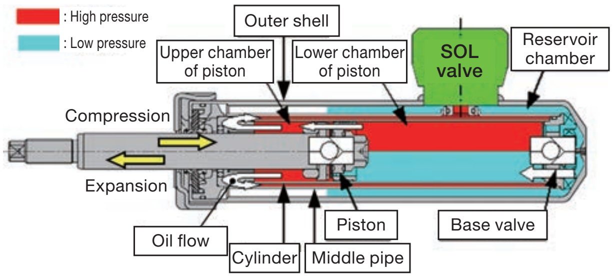

Fig. 6 Triple tube uniflow configuration

In this configuration, a piston valve and base valve basically have the sole function of a check valve, and damping force is mainly generated by the SOL valve. During both compression and expansion strokes, the upper chamber of piston is under high pressure while the space between the cylinder and the middle pipe to the SOL valve is under control pressure. The oil is then discharged from the SOL valve to return to the reservoir chamber. During expansion stroke, the amount of oil equivalent to the changed volume of the lower chamber of piston is supplied via the base valve.

3.2 Control Methods

The SOL valve uses a pilot type electromagnetic proportional relief valve that can operate the valve body by using difference in pressure between the fluids. The pilot valve can be controlled in two ways: pressure control and valve opening area control. Fig. 7 shows damping force characteristics.

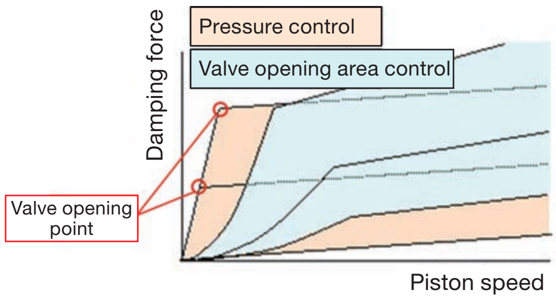

Fig. 7 Damping force characteristics for pressure control and valve opening area control

In the case of pressure control, the control current is used to control the pressure in the pilot chamber (pilot pressure). The relationship between damping force and piston speed can be represented by a fixed slope over the entire range from SOFT to HARD damping although the valve opening point varies. Therefore, even if damping force is raised in the low-speed region for higher car handling stability, damping force at mid or high-speed region will be curbed without degrading ride comfort.

This feature of a fixed slope is the same as a feature of a damper that integrates a standard passive damper and variable damper that produces a damping force by solely relying on the electric current (Fig. 8).

On the other hand, in the case of valve opening area control, the control current is used to control the opening

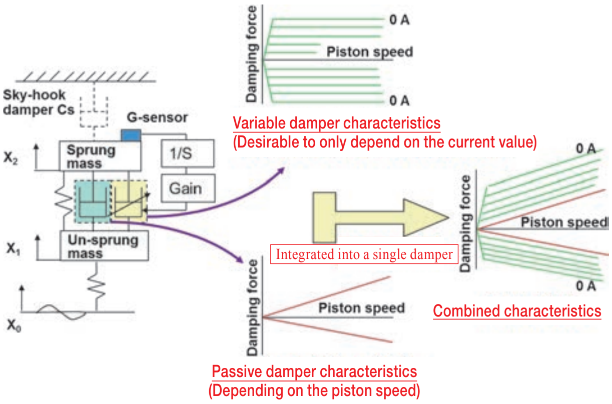

Fig. 8 Pressure control and its controllability

area of the pilot valve. The slope of the relationship between the damping force and piston speed varies with the control current. The damping force is decided by both the current and piston speed.

In implementing semi-active control as seen in Skyhook dampers using these damping force control methods, if the damping force can be only set by the electric current as seen in pressure control, the detection of the piston speed is no longer necessary. This is an advantage of this method. The valve opening area control requires the related mechanical parts to be made with high precision that results in higher cost.

All these control systems have been applied to commercial products. In this development, the pressure control system has been used from the viewpoints of controllability and mechanical part precision, and relatively easy achievement of compatibility between handling stability and ride comfort.

3.3 SOL Valve Configuration

Fig. 9 a simplified model of the SOL valve is shown in shows and Fig. 10 the principle of operation shows.

The flow of hydraulic oil controlled by the SOL valve is explained below.

Pilot flow: Part of the main flow passes through the pilot orifice provided in the plug and flows into the pilot chamber. The oil pressure therein is controlled to a pressure set by the solenoid thrust. When the pilot pressure exceeds the set pressure the poppet valve is pushed up and the oil is discharged from the pilot chamber.

Main flow: For a low flow (medium pressure = main pressure), the main valve is made up of the laminated leaf valve and the spool, and receives the medium pressure on the bottom and the pilot pressure on the top. When the medium pressure reaches the product of the pilot pressure and the preset pressure boost ratio, the leaf valve is pushed up to discharge the oil to the reservoir chamber. When the flow rate increases (medium pressure < main pressure), similar movement takes place above and below the movable disc located in the lower section, which pushes up the movable disc to discharge the oil to the reservoir chamber.

Fig. 11 a typical illustration of damping force characteristics shows.

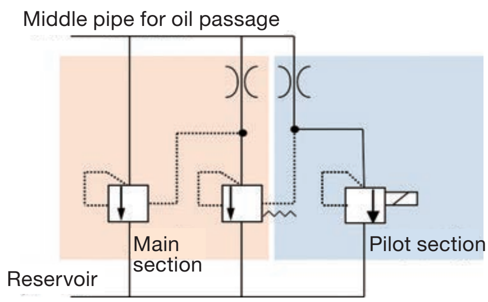

Fig. 9 Simplified model of SOL valve

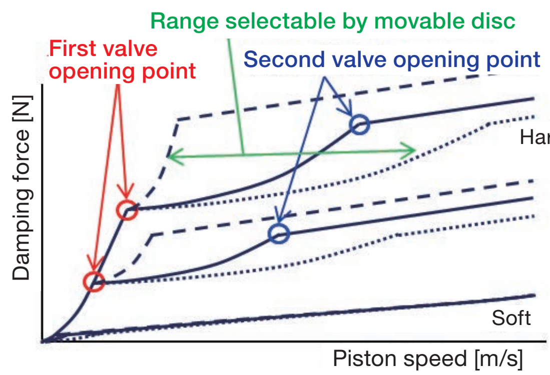

Fig. 11 Illustration of damping force characteristics

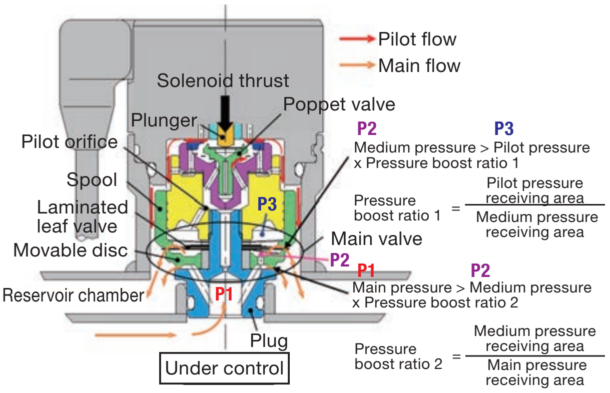

Fig. 10 Principle of operation

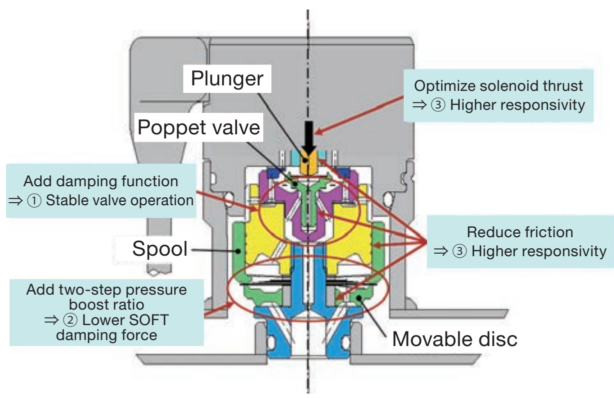

Fig. 12 Development target parts

3.4 Development of SOL Valve

The following challenges extracted in the component development valve are resolved in the SOL valve dev. Fig. 12 the target parts shows.

① Stable operation for valve (improved damping force oscillatory wave form)
② Lower SOFT damping force
③ Higher response

① Stable operation for valve (improvement of damping force oscillation)

In the component development stage, the shock absorber, was found to have a abnormal damping force oscillation in a shaking test. This was caused by self-excited vibration of the poppet valve. A damping function has been added to the poppet valve to suppress the vibration, because it is generally effective to damp the poppet valve. Fig. 13 shows an enlarged view of the poppet valve.

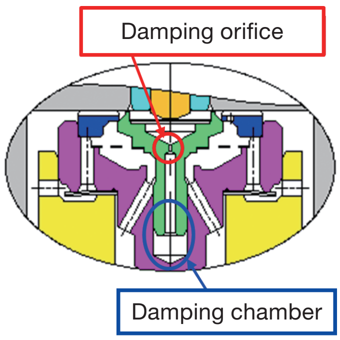

Fig. 13 Enlarged view of poppet valve

② Lower SOFT damping forces

In the component development stage, the main valve was designed to be opened in a single step, and the opening pressure was set high to ensure a wide adjustable range for HARD damping force. This design inevitably made SOFT damping force higher too. To solve the problem, the valve configuration was modified to allow the valve opening pressure at two different levels. In the low-speed region, the valve opening pressure was kept low to lower the SOFT damping force. In the normal speed region, the second opening pressure can be set to a higher level. In addition, two valve ports were provided to ensure a larger opening area, suppressing the increase in damping force in the mid-speed and high-speed regions.

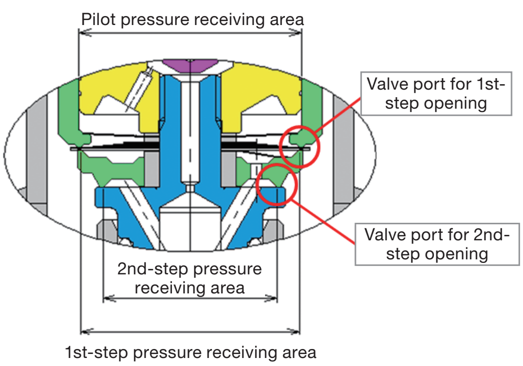

Fig. 14 Main valve section

These improvemented ride comfort. Fig. 14 the main valve section is illustrated in shows.

③ Higher response

In addressing the higher response challenge, the development team considered it effective to improve the solenoid thrust response and reduce the sliding resistance of the plunger, the poppet valve, the spool and the movable disc during their interaction within the SOL valve.

In terms of the solenoid thrust response, a dynamic behavior analysis was conducted using a quality engineering approach (Figs. 15 and 16). As a result, the analysis revealed a tendency that the magnitude and response of the solenoid thrust are trade off. Then, the solenoid thrust was set to a minimum level to improve response. Geometry and material of the sliding part are optimized to ensure a lower sliding resistance. The design implemented smooth movements of the sliding parts and achieved higher response.

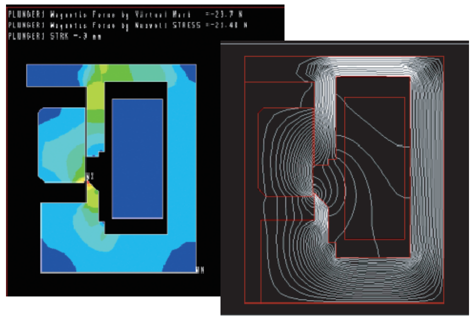

Fig. 15 Dynamic behavior analysis (example)

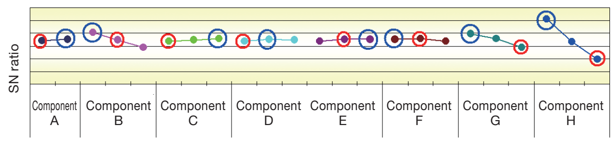

Fig. 16 Cause and effect diagram based on quality engineering (example)

4 Development of Middle Pipe

The middle pipe (Fig. 17) is an indispensable component of adjustable SA with external SOL. A side-hole oil passage protruding from the pipe introduces the hydraulic pressure generated in the SOL valve into the upper

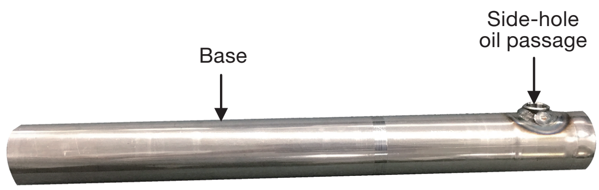

Fig. 17 Appearance of middle pipe

chamber of the piston.

The middle pipe must have sufficient pressure fatigue strength (Fig. 18). With the wide adjustable range of damping force and uniflow configuration, the middle pipe is exposed to repetitive pressure fluctuations as a damping force is generated during each expansion/compression stroke. This requires the middle pipe to have not only static strength but also sufficient fatigue strength.

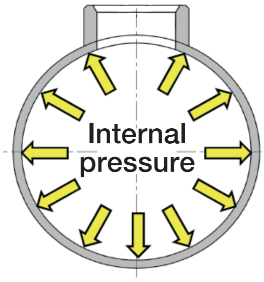

Fig. 18 Pressure applied to middle pipe

When the middle pipe receives with an internal pressure (repeatedly), a radial tensile force (generally called a "hoop stress") occurs. The repetitive radial force may result in stress concentration particularly around the side-hole oil passage, causing cracks to depressurize the oil, and the function to produce damping forces may be lost (Fig. 19).

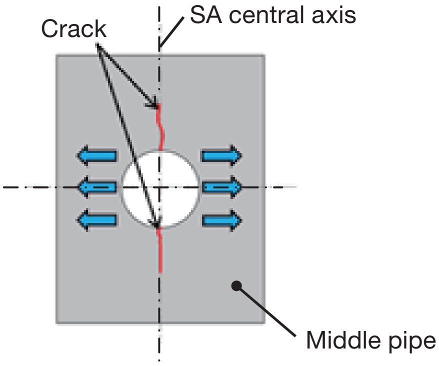

Fig. 19 Cracked middle pipe

To reduce the stress, it is generally effective to increase the wall thickness of the middle pipe. However, the development team needed to guarantee strength without increasing the wall thickness with concerns about mass increase and constraints on the perimeter space (Fig. 20).

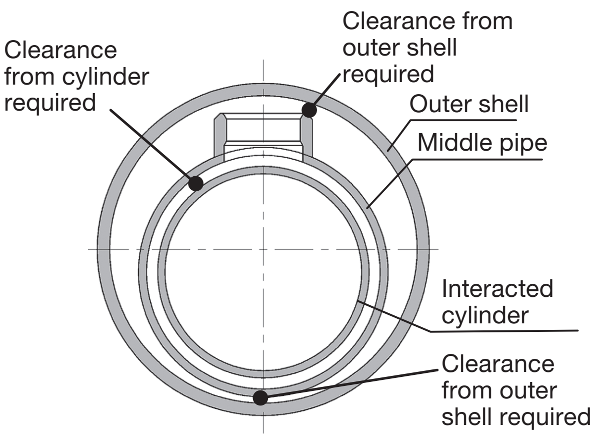

Fig. 20 External/internal casing space constraints during assembly

As a means to ensure stress relaxation, the finite element method (FEM) stress analysis and verification using actual vehicles were conducted. As a result, the side-hole of the middle pipe was modified from the original round hole to a flat oval hole, successfully reducing the maximum stress in the stress concentrated part by about 40 percent (Fig. 21). By using the flat oval side-hole, the middle pipe eventually ensured the required strength with a thin wall of 1.3 mm regardless of the original requirements for the wall thickness of about 2.2 mm to satisfy the specified pressure resistance (Fig. 22).

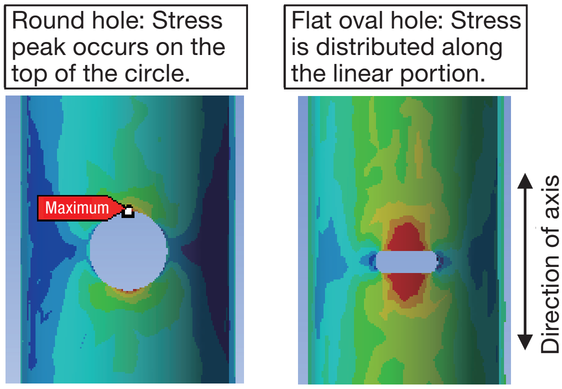

Fig. 21 Flat oval hole stress analysis (example)

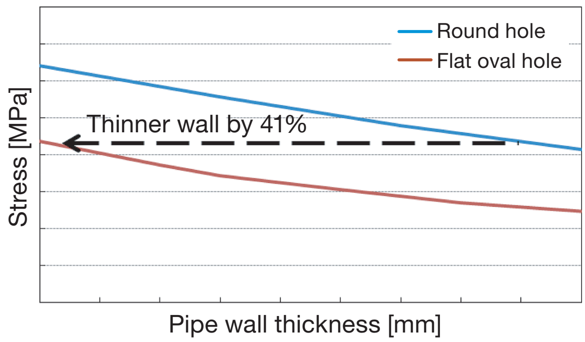

Fig. 22 Relationship among hole shape, wall thickness and pipe stress

5 Current Application

This developed product was put into mass production in November 2016. Currently, adoption of the product for many vehicle models is considered and development for adaptation is on-going. The product is recognized as a high-value added product, separated from the standard shock absorber. KYB plans to roll it out as the company's future key product. Both the number of vehicle models using the product and production are expected to increase (Fig. 23).

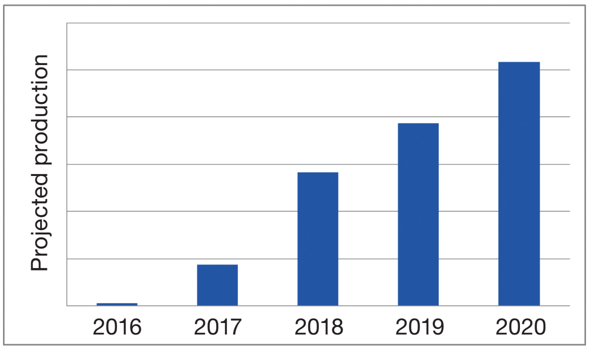

Fig. 23 Projected production of damping force adjustable SAs with external SOL

6 In Closing

KYB has developed adjustable SA with external SOL that can be easily installed to vehicles and makes it possible to ensure both handling stability and greater ride comfort. KYB is also going to promote the development of adjustable SA with internal SOL as another product model to meet additional customer needs.

Finally we would like to cordially thank those who have cooperated with us.

References

1) KIMISHIMA: Development of High Damping Force Piston Valve for Extra Low Velocity, KYB Technical Review No.54 (April 2017)

Author

KAMAKURA Ryosuke

Joined the company in 1994.
New Products Development Dept.,Engineering Headquarters, Automotive Components Operations.
Engaged in shock absorber components development.

FURUTA Yusuke

Joined the company in 2000.
Design Sect. No.1, Engineering Dept., Suspension Headquarters, Automotive Components Operations.
Engaged in shock absorber development.

MORI Toshihiro

Joined the company in 2006.
Design Sect. No.1, Engineering Dept., Suspension Headquarters, Automotive Components Operations.
Engaged in shock absorber development.

TOMITA Kohei

Joined the company in 2012.
Design Sect. No.1, Engineering Dept., Suspension Headquarters, Automotive Components Operations.
Engaged in shock absorber development.