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KYB Corporation

KYB TECHNICAL REVIEW No. 63 OCT. 2021

ISSN 1880-7410

KYB TECHNICAL REVIEW

OCT. 2021
No.63

KYB Corporation

(Kayaba Industry Co., Ltd. employed “KYB Corporation” as the popular name from October 1st, 2015.)

As of August 1, 2021

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Foreword

Motor Technology is Still Interesting

KANO Yoshiaki*

I am very proud to have this opportunity to write the Foreword for the KYB Technical Review No.63 published by KYB Corporation, which has broad operations mainly related to hydraulic equipment.

Readers of this Foreword are probably involved in manufacturing in some individual way, depending on their position in concrete efforts. Many may have felt or been strongly moved by the fact that manufacturing offers convenience, functionality and/or effectiveness. In relation to the motor technology that supports the Japanese manufacturing industry, I would like to describe in this Forward how I have been fascinated by the technology, what I am studying about it now, and what future motors will be like.

1. Encounter with motors

In my childhood, my daily life was spent among "vivid" learning materials for production. As my family were part-time farmers, I saw how rice grains were threshed in autumn. I also had the opportunity to see stone craftsmen striking rocks with push hammers in Ishiya-machi, Okazaki City, where I used to live and which is famous for its marble stone. I was surrounded by many things that would motivate my curiosity about manufacturing. Today, we live in a society flooded with meticulously made products. I am rather worried about today's children, who are given virtually no occasion to repair things themselves and could grow up without feeling anything about production.

When I was a third-year university student, I was enrolled in a lecture on electric equipment, including direct-current motors. I studied this subject with enthusiasm, probably because I had kept my passion for manufacturing ever since my childhood. Unlike the other subjects I was enrolled in during the year, the electric-equipment curriculum greatly fascinated me because, in addition to the fact that the curriculum covered "motors," which are one of the historical industrial products, I thought it was a discipline of "genuine engineering" that integrates different theories, including electromagnetics as well as material science, mechanical engineering and control technology. Motors, which have a history as long as nearly 200 years, even now account for about 50 percent of power consumption. I think that the motor is an electromechanical energy conversion device that can hardly be substituted by any other device, in that they have a quite good balance among cost, reliability and power density. At that time, the world's first mass-production hybrid car "Prius" happened to be released to the market. I had had an impression that a motor was a low-technology product made of iron and copper, but I changed that impression when I encountered the car designed based on a brand-new concept equipped with a newly-structured motor. Eventually, I came to recognize motors as being extremely interesting high technology. That experience also made me want to be involved in research on the front line of the field. I then made a decision to join one of the few laboratories engaged in motor research and development.

2. My research activity in university

Neary 20 years have passed since I became acquainted with the world of motors under the theme of computer-aided design of application-oriented electric motors in the master’s course I was doing. The concept of application-oriented electric motors was proposed in 1995 by Nobuyuki Matsui, who is an ex-President of Nagoya Institute of Technology and also my mentor. One example of application-oriented electric motors is the hybrid car drive motor. To deliver the highly demanding performance in the limited space of the engine room, even the motor structure and mechanism are specifically designed from the beginning according to required specifications. The concept of application-oriented electric motors was based on an idea that, unlike traditional general-purpose motors, motors developed in this way would virtually be future-proof motors, and that a shorter design lead time was critical to open up such a world. In other words, computer-aided design enabling general design, detailed design, prototyping and evaluation processes to be completed in a short period was indispensable. As the computing power had dramatically advanced, it certainly became easier to clarify electromagnetic phenomena, including three-dimensional magnetic saturation, thereby enabling specially-designed advanced motors to be used for various applications, as forecasted by my mentor. Now, with a

*Associate Professor, Daido University

focus on material technology that may determine the advancement of motors, I am trying to create a motor technology that satisfies the demands of the next era, under the belief that new material will be a key to enhancing the motor characteristics.

3. Future motors

Recently, motors have found wider applications and more users in additional fields to activate product development, allowing motors to be more easily used by anybody. Behind this trend is the penetration of Internet of Things (IoT). We have just entered the age of "Networked Appliances" and "Connected Cars," where home appliances, automobiles and various other applications are networked. How will motors used in such scenarios evolve? For example, air-conditioners may no longer need to have the capability of quickly heating/cooling a room if their controls can be remotely operated by users before they return home. For automobiles, your car may never hit an object even if you, in an extreme case, fall asleep while driving, or you can drive anywhere while seeing real-time video of the scenery. That is, your car is robotized. Perhaps such an age may come. If so, the motor requirements, including required performance, will substantially change, and we will need to create new technologies in response to the changes. Motor technology is still interesting, as it can create new values to adapt to the modern social structure and ever-changing lifestyle. You are unable to take your eyes off the advancement of the technology.

Technology Introduction

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

ABE Tomoyasu, DOI Kohei

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.

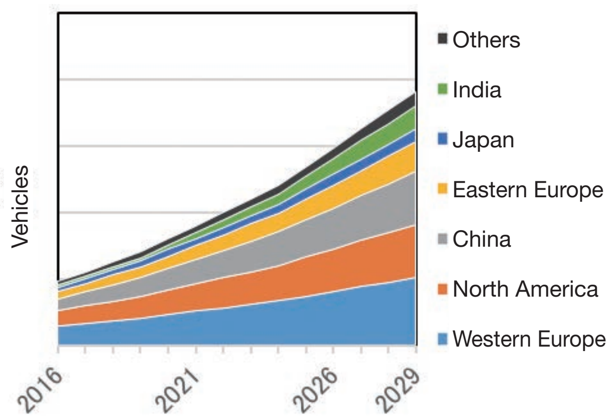

Fig. 1 Projected number of vehicles equipped with semi-active suspensions

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)

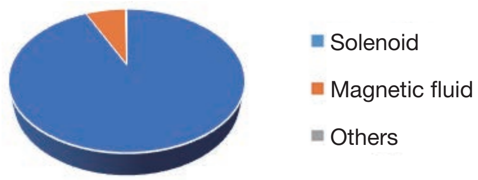

Fig. 2 Share of damping force adjusting system (FY2019)

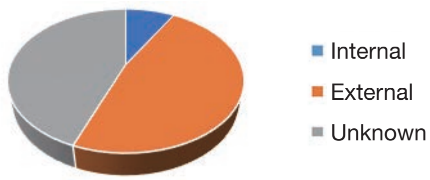

Fig. 3 Share of damping force adjusting valve position (FY2019)

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].

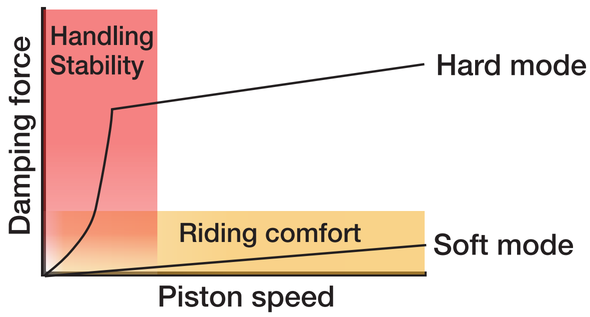

Fig. 4 Damping force of adjustable SA

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.

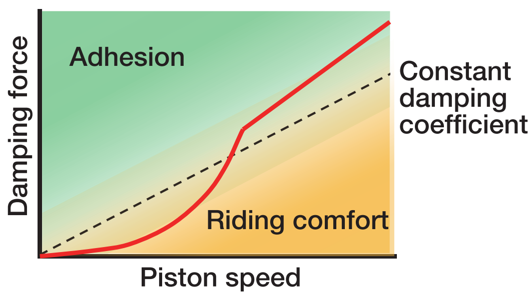

Fig. 5 Aim of improved soft-mode damping force and damping coefficient

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].

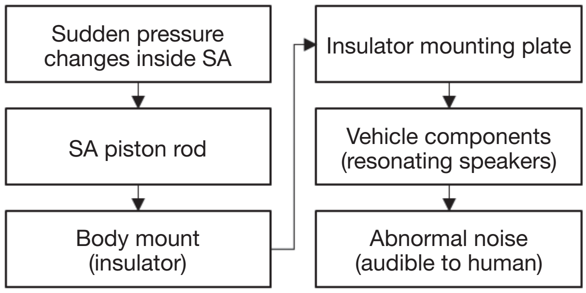

Fig. 6 Rattling noise transfer system

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.

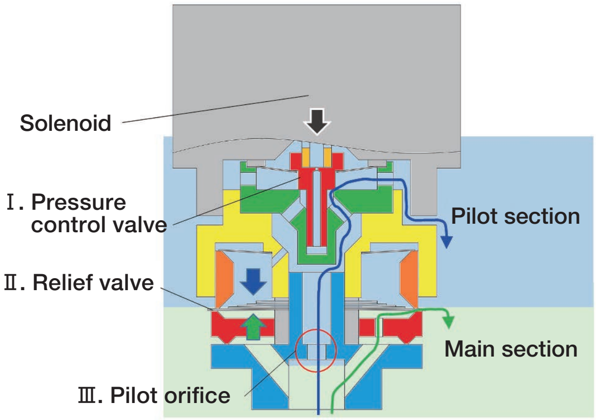

Fig. 7 Simple model of SOL valve

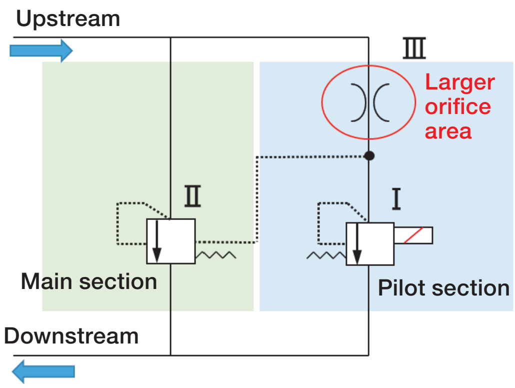

Fig. 8 Hydraulic circuit diagram of SOL valve

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

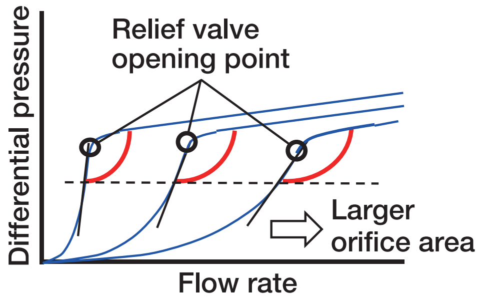

Fig. 9 Orifice area and pressure change

experiencing the sudden load change, contributing to lower rattling noise.

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.

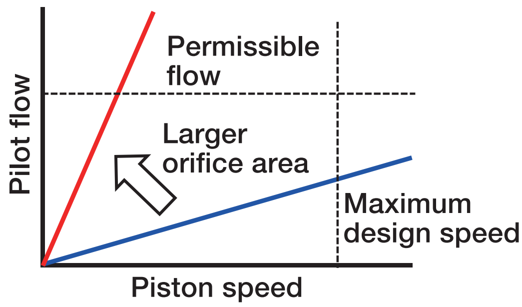

Fig. 10 Problem with conventional design

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.

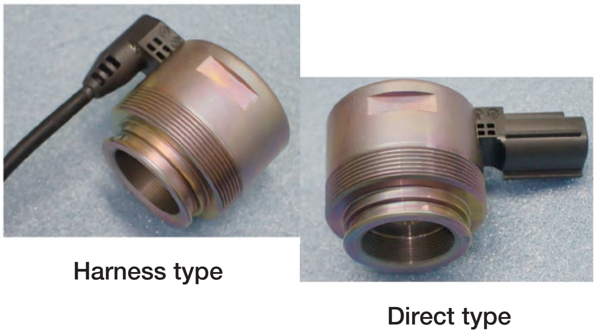

Photo 2 Appearance of new solenoid

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.

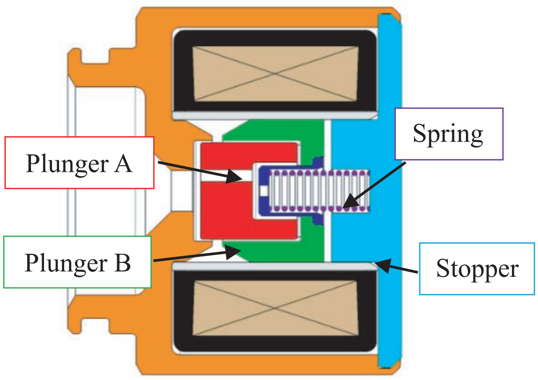

Fig. 11 Behavior of DP solenoid (non-energized state)

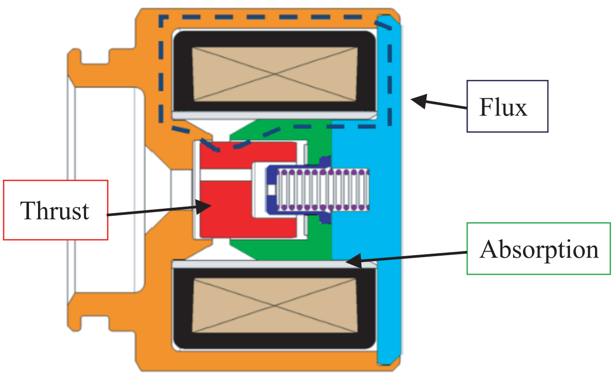

Fig. 12 Behavior of DP solenoid (energized state)

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.

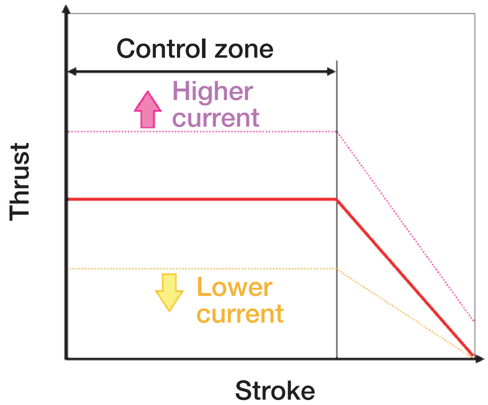

Fig. 13 Conceptual image of proportional solenoid thrust characteristics

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.

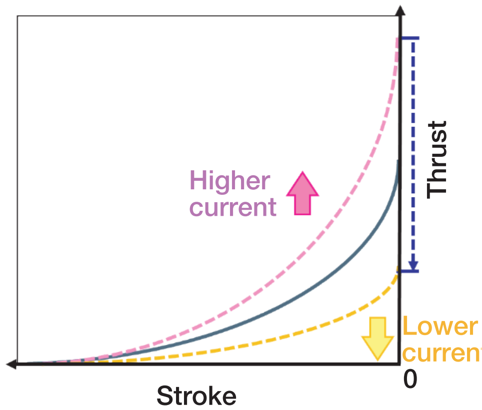

Fig. 14 Conceptual image of On/Off solenoid thrust characteristics

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)

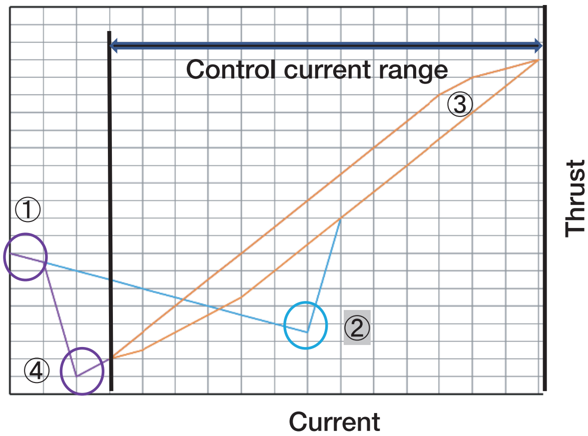

Fig. 15 Current-thrust characteristics diagram (conceptual image of operation)

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.

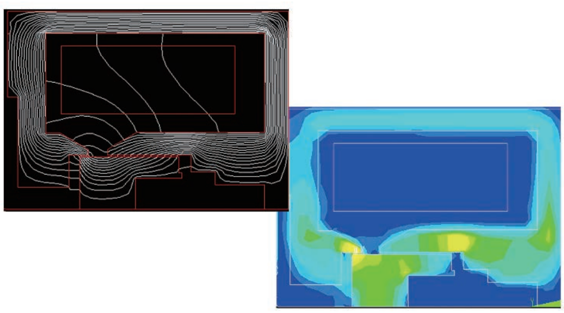

Fig. 16 Conceptual image of magnetic analysis model

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.

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.

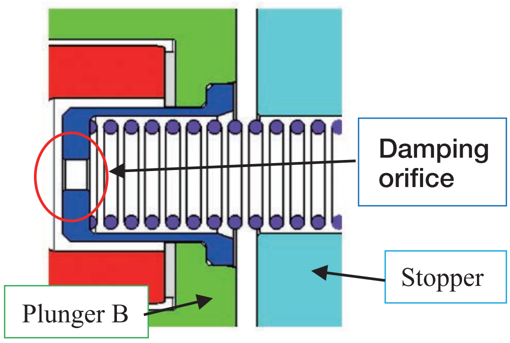

Fig. 17 Enlarged view

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

1) KAMAKURA, FURUTA, MORI, TOMITA: Development of Externally-Mounted Shock Absorber with Adjustable Solenoid Damping Force, KYB Technical Review No.55 (October 2017).
2) UENO, MATSUSHITA: Response Improvement of Shock Absorber with Proportional Solenoid Damping Force Adjustment by Using Magnetic Field Analysis, KYB Technical Review No.57 (October 2018).
3) OTA: Development of Electronically-Controlled Suspension for Automobiles in the KYB Group, KYB Technical Review No.60 (April 2020).
4) Editor - KYB Corporation: Structure, Theory and Evaluation of Automobile Suspensions, p.171 (2013).

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Technology Introduction

Development of Active Suspension by KYB

INAMITSU Kazutaka, HORI Masatoshi

1 Introduction

The active suspension, which is sometimes called the "ultimate" suspension, is a suspension system that can deliver both high-level riding comfort and high-level handling stability simultaneously. KYB developed a hydropneumatics Note 1) -based hydraulic active suspension jointly with Nissan Motor Co., Ltd., which was fitted onto the INFINITI Q45 Note 2) which was released to the market in 1989 (Photo 1). In Japan, however, the automobile industry shifted from the age of pursuing higher performance to the age of focusing on environmental performance, cost effectiveness and usability. The product was no longer used in Nissan's vehicles in the early 2000s.

Photo 1 INFINITI Q45 (left)
KYB hydraulic active suspension (right)

In Europe, Daimler AG launched its flagship vehicle model equipped with active suspensions in 1999 and has continued using them through performance improvement since then. Other active-suspension-related technologies have also been commercialized, including the active stabilizer that is specifically designed to suppress vehicle roll during cornering.

Another variant of active suspensions is the so-called semi-active suspension. This suspension system delivers limited functionality of active suspensions to enable both performance and cost to go hand in hand and are popularly used in the D-segment (Upper Medium cars) as well as in the C-segment (Lower Medium cars) Note 3) mainly in Europe.

Today, some other similar systems have also been devised. One is a system based on semi-active-suspension equipped with an energy source to deliver an active suspension function. Another is an active suspension system that can recover the damped energy of the suspension to save on power consumption. In addition, an electric active suspension system that uses a motor as its power source without using hydraulic power has already been commercialized. This implies that the industry is almost back to the age of active suspensions.

Since the development of the initial hydraulic active suspension, it has been a long-time challenge over more than 30 years for the Engineering Division of KYB to implement an ultimate active suspension. This paper introduces an active suspension system that KYB has designed and prototyped as a Proof of Concept (POC).

Note 1) The term "hydropneumatics" refers to a suspension system that uses the hydraulic power to transfer forces and also uses the gas compression as a spring mechanism. (The use of gas as a spring helps prevent the transfer of small vibration to the sprung mass (practically, the vehicle body), which is generally considered to offer superior ride comfort.)

Note 2) "INIFINITY Q45" is a trademark owned by Nissan Motor Co., Ltd.

Note 3) The term "segment" here refers to the European classification of passenger cars based on car size criteria.

2 What is Active Suspension?

Let us briefly explain suspensions before diving into the subject. A suspension mainly consists of an arm, a suspension spring and a shock absorber. These elements move according to relative movement of the sprung components and the unsprung components (practically, the wheel). The input from the road surface is absorbed by the suspension spring, and the vibration energy of the spring is damped by the shock absorber. A suspension system equipped with the most common shock absorber is called a passive suspension.

For passive suspension, the damping characteristics of the shock absorber is uniquely defined by the input speed. Tuners usually have to find a good level of ride comfort by striking a balance among related factors in the vehicle development stage.

A semi-active suspension has a shock absorber with an integral damping force adjusting mechanism, thereby enabling the vehicle to adjust the damping characteristics according to the road condition.

Unlike the system above that passively outputs force in response to input from the road surface, the active suspension has a mechanism that actively outputs force with its own energy source. How these different suspensions can behave in response to the vehicle movement is simply illustrated in Fig 1.

		Sect.1	Sect.2	Sect.3	Sect.4	Sect.5	Sect.6	Sect.7	Sect.8	
Sprung displacement		None	Up	Up	Down	Down	Up	Down	None	
Direction of movement of SA		–	Comp.	Reb.	Reb.	Comp.	Reb.	Comp.	–	
Passive	Amount and direction of force	–	↑	↓	↓	↑	↓	↑	–	Uniquely defined damping force
Semi-active		–	↑	↓	↓	↑	↓	↑	–	Adjustable damping force
Active		–	↓	↓	↑	↑	↓	↑	–	Vibration damping with active force

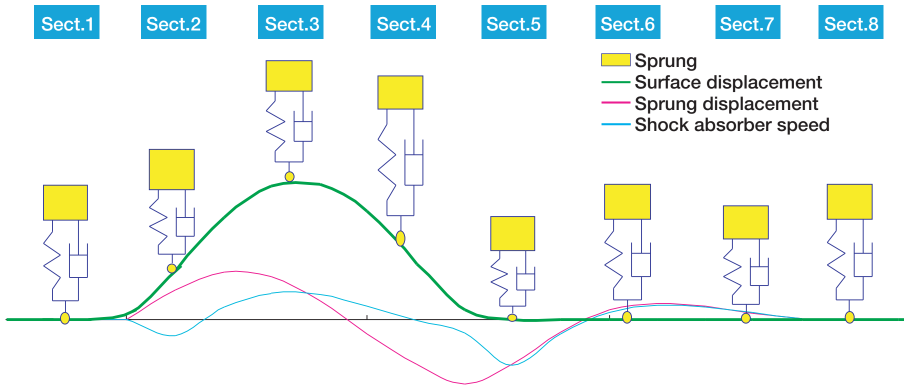

Fig. 1 Characteristics of each suspension during driving

In the sections 2 and 4, in contrast to the passive suspension, the semi-active suspension changes the amount of the damping force to prevent the sprung components from moving. On the other hand, the active suspension only focuses on the movement of the sprung mass to be controlled regardless of whether the shock absorber extends or contracts. It can drastically reduce the ratio of sprung displacement (transfer characteristics) by changing the amount and direction of the force. Unlike the "vibration damping" achieved by the semi-active suspension, the active suspension can offer a state that is as close as possible to "immobilization".

These characteristics are illustrated in Fig. 2 as performance of a single shock absorber. The diagram expresses forces (resistance and exciting forces) according to the relative speed of the sprung and the unsprung in response to input from the road surface. Particularly, the zones colored in orange represent the characteristics specific to the active suspension.

The force characteristics of these types of suspensions are summarized in Table 1. According to the table, only the active suspension can deliver a given amount of force in either direction.

Fig. 3 shows the vibration transfer ratio of these suspensions, i.e., how much they can suppress vibration by using their forces. While the semi-active suspension cannot limit vibration to the road surface displacement or lower at around the resonance frequency of the sprung components (not more than 1 in Fig. 3) the active suspension can do so.

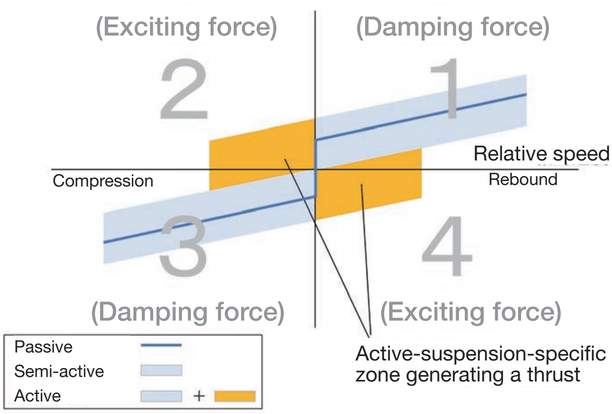

Fig. 2 Forces generated by various shock absorbers

Table 1 Force characteristics of various suspensions

Type	Amount of force	Direction of force
Passive	Uniquely defined	Fixed (resistance)
Semi-active	Variable	Fixed (resistance)
Active	Variable	Switchable (resistance/exciting)

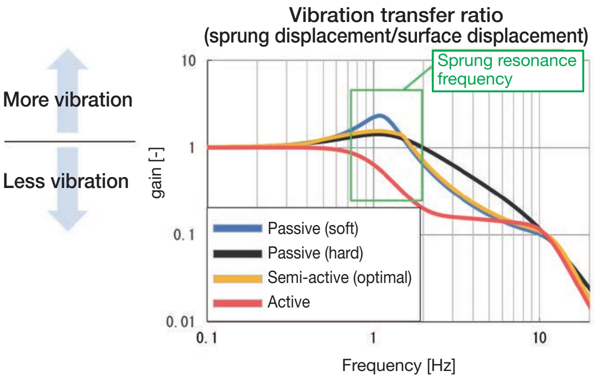

Fig. 3 Example of transfer ratio of vibration from road surface for various suspensions

3 Aim of Development

As described above, the active suspension can freely control the sprung mass. Now, it is necessary to consider of how the sprung components should be moved for good vehicle control. Is it right to immobilize the sprung at all? Conversely, could it make passengers feel uncomfortable? From the viewpoint of vehicles, we had difficulty determining which was the right answer based only on the results of simulation. This necessitated us to establish a vehicle testing scheme that allows people to actually feel the ride comfort of the vehicle controlled in different ways. We therefore decided to build an experimental vehicle.

4 Overview of Experimental Vehicle

4.1 Description of Experimental Vehicle

The requirements for a base experimental vehicle include:

① that the vehicle must be equipped with a high-voltage battery to drive the motor, and;

② that the vehicle must have semi-active suspensions.

A hybrid car of the E-segment (executive cars) meeting the requirements above was selected (Photo 2). The car equipped with highly-responsive, high-performance semi-active suspensions was determined to be appropriate for performance comparison.

4.2 Configuration of Suspension System

Fig. 4 shows the configuration of the suspension system for the experimental car. The system is considerably different from the conventional hydraulic active suspension system in:

Photo 2 Experimental vehicle with active suspensions

① the motorized power source rather than the engine;

② higher responsiveness achieved by excluding the use of hydropneumatics, and;

③ a simple structure for lower cost.

To efficiency build an active suspension system for the experimental vehicle, the control valves were fabricated based on existing internally-developed products, and the motor and other components that can be implemented with general-purpose products were purchased externally, resulting in reduced man-hours.

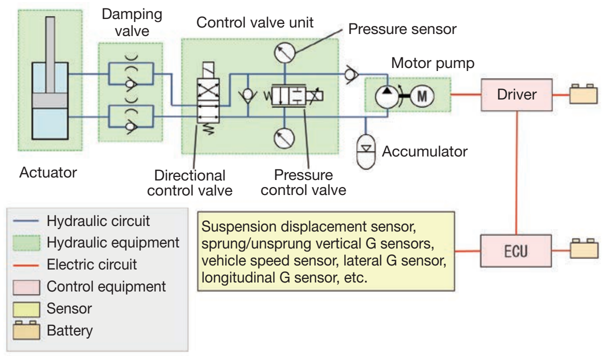

Fig. 4 System configuration

4.3 Concept of Vibration Control

As a general vibration control logic, the Skyhook control [1] is conventionally well known. In this development effort, we aimed at further improving the existing vibration control. To this end, we discussed measures to reduce vibration using a quarter vehicle model with input from the road surface and an external force applied to the sprung (corresponding to the inertial force of the actual vehicle) in order to determine the mechanism by which the sprung components are vibrated (Fig. 5).

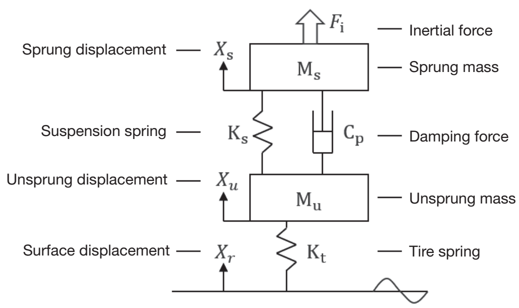

Fig. 5 Monocycle model

The equation of motion of the sprung vibration shown in Fig. 5 can be expressed by:

$$M_s\ddot{X}_s = -C_p(\dot{X}_s - \dot{X}_u) - K_s(X_s - X_u) + F_i \quad (1)$$

In equation (1), the 1st term of the right-hand side represents the damping force of the shock absorber, and the 2nd term the spring force of the suspension spring. Since the input from the road surface is transferred to the sprung via the unsprung, equation (1) can be converted into a block diagram, shown in Fig. 6, with the unsprung displacement X_u and the inertial force F_i taken as input and the sprung displacement X_s taken as output, where "s" indicates the Laplace operator.

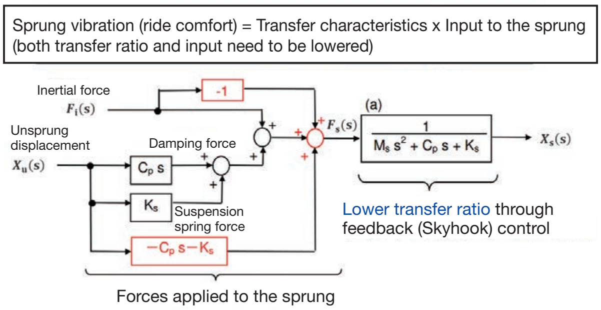

Fig. 6 Block diagram of equation of motion of the sprung

To decrease the sprung vibration, it is necessary to increase the damping force in the block (a) (= sprung vibration control) and decrease the input including C_pX_u, K_sX_u and F_i (= lower input to the sprung).

According to this vibration mechanism, it is effective to take measures to decrease the sprung vibration as compiled in the control policy shown in Table 2. We established a set of control logics to satisfy the policy.

Table 2 Control policy

№	Method
1	Add a force that depends on the sprung speed
2	Reduce the force applied to the sprung via a shock absorber with the unsprung vibration as input
3	Reduce the force applied to the sprung via a suspension spring with the unsprung vibration as input
4	Reduce the force applied to the sprung with the inertial force

5 Performance Verification

5.1 Description of Simulation

First of all, the effect of vibration control was simplified as in a quarter vehicle model shown in Fig. 7 before verification with a full vehicle. Fig. 8 shows the results of simulation using the monocycle model. For simulation of different control patterns related to ride comfort, the methods No.1, 2 and 3 in Table 2 were combined and the resulting data was checked for each control method. The simulation revealed that the model offered substantial effects of vibration control at around the sprung resonance frequency (around 1 Hz). It also showed that the ride comfort was not apparently worsened even at around the frequency (10 Hz) characterized by the so-called "brubru" vibration, proving good control effect. However, it should be remembered that the simulation is only a simplified approach accompanied by calculation based on an assumption that the model just uses an ideal actuator (no delay).

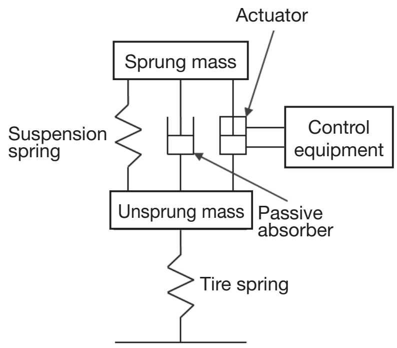

Fig. 7 Quarter vehicle model of active suspension

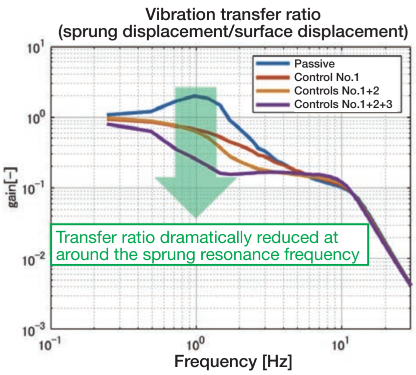

Fig. 8 Simulated sprung vibration control characteristics

5.2 Bench Test

Next, a quarter vehicle suspension system was fabricated to take measurements using a tester (Photo 3). The results of the test showed a trend similar to that obtained through the simulation (Fig. 9). From these test results, the suspension system for the experimental vehicle to be fabricated at this time was verified to have a substantial vibration control effect as initially assumed.

5.3 Testing on Actual Vehicle

5.3.1 Construction and Safety of Actual Vehicle

After verification of the suspension system for its vibration control effect, the system was mounted on the actual experimental vehicle. Before testing, the vehicle, which was unmanned for safety, was subjected to simulated vibration from the road surface by means of a 4-poster vehicle tester to make sure that the system will not be unstable. Furthermore, to ensure that the vehicle can stop the suspension system safely if an unexpected problem

Photo 3 Quarter vehicle tester

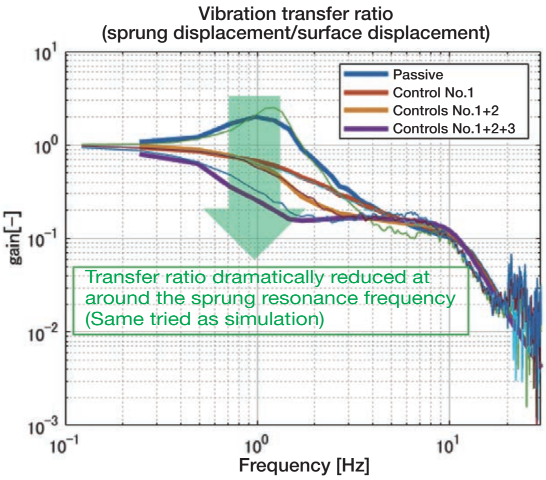

Fig. 9 Measurements using quarter vehicle tester

occurs, an emergency switch was installed so that the power supply to the motor can be interrupted in case of emergency.

5.3.2 Results of Measurement with Actual Vehicle

This experimental vehicle was run on KYB's test driving courses (Figs. 10 to 13, Photo 4). For evaluation of ride comfort, a test driver drove the vehicle on a sine wave road (focusing on the sprung resonance frequency), on a random input road, and on an EU country road (a road surface simulating a typical country side road in Europe). To verify the handling stability (for any sprung variation caused by turning the steering wheel), the driver changed lanes. For the purpose of obtaining reference conditions for comparison purpose, the same measurement was made on the original vehicle (equipped with semi-active suspensions).

The test on the actual vehicle showed the following results:

① Vibration at around the sprung resonance frequency was substantially lower than that for the vehicle with semi-active suspensions.

② On the EU country road with a combination of undulations and slight vibrations, the motion associated with large undulation were eliminated while the harsh caused by slight vibrations remained, proving the vibration control effect at around the sprung resonance frequency.

③ The substantially reduced roll angle made the tires contact effectively with the ground, leading to stable driving.

However, some challenges were found with the experimental vehicle. The ride comfort was worse on a bumpy road (because the control failed to compensate for vibration from the road surface due to insufficient responsiveness of the control valve). Another challenge was the noisy motor that had been scaled up in performance for

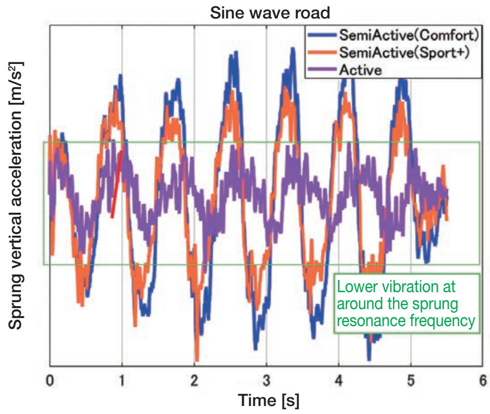

Fig. 10 Sine wave road

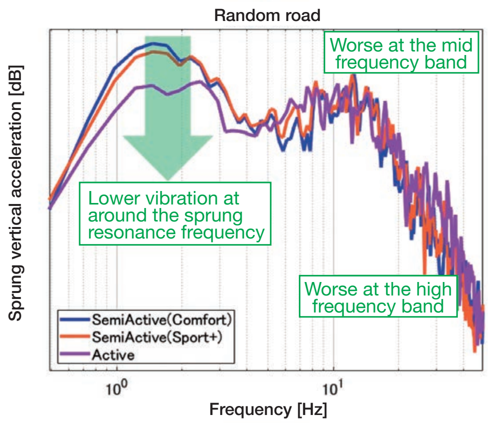

Fig. 11 Random road

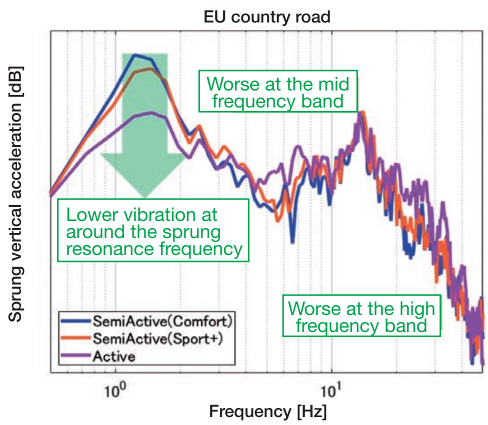

Fig. 12 EU country road

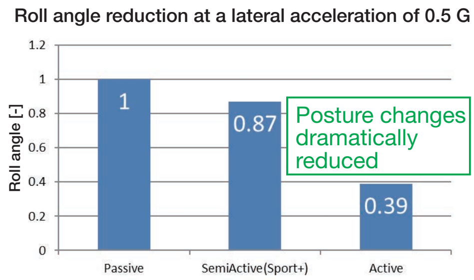

Fig. 13 Lane change

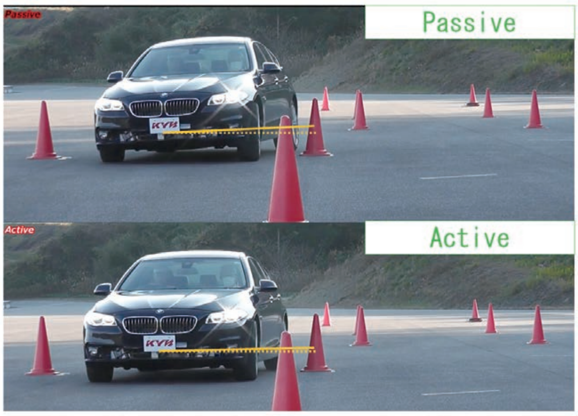

Photo 4 How the vehicle changes lanes

the purpose of verification. Still, the originally assumed performance level was attained.

5.3.3 Results of Test Drive of Actual Vehicle

In a test ride by those concerned, test drivers gave various feedback, for example, "the sprung motion was definitely limited, and I felt very flat, which could not compare with semi-active suspensions," "I felt easy as my head was not swung," and "very comfortable with no swing back."

6 Conclusions

In this activity, we:

① discussed the requirements for implementing the active suspension system and established the system;
② established and verified a set of control logics for improving the vibration control;
③ built a simulation environment for verifying the control effects;
④ fabricated and evaluated an experimental vehicle to allow drivers to feel the effect of the active suspension system; and,
⑤ broadly collected opinions of drivers in a test ride.

Particularly, we not only simulated the control technology but also actually mounted it on the experimental vehicle to provide an environment in which we could collect opinions and evaluation from a broad range of people. This forms the base for us to be able to discuss how the active suspension should be.

When pursuing an active suspension product capable of freely controlling the sprung components, the existence of the experimental vehicle is invaluable in considering the feeling and sensitivity of drivers. This is a meaningful activity toward the future.

With an aim of developing indices for the sensory evaluation of actual vehicles, Experiment Dept., KYB, has launched an activity for quantifying the sensitivity of drivers. As a team KYB, we will try to improve the development capability.

7 In Closing

People say that the automobile industry has entered a period of so big change that occurs once every 100 years. With notable keywords including "Connected," "Autonomous," "Shared & Service" and "Electric" taken into account, motor vehicles are expected to evolve into mobility equipment with various added values, not just a means of transportation. As one of the ideas for contributing to such a society, we have proposed the potential of active suspensions. In order to send an ultimate suspension out into the world again, we want to develop an active suspension system meeting the needs of the times while deepening our understanding of the system, control and sensitivity. Finally, we would like to take this opportunity to sincerely thank all those concerned who gave us guidance and cooperation for this development effort.

References

1) Alonso TORRES: Semi-Active Suspension, Extending the Limits, KYB Technical Review No.56 (April 2018).

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Technology Explanation

Development of an Equipment Predictive Maintenance System

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Abstract

In the manufacturing industry, maintenance activities for machines and equipment operating at production sites are essential for maintaining stable production of high-quality products. The concept of equipment maintenance can be broadly divided into three categories: breakdown maintenance, preventive maintenance and predictive maintenance. In recent years, predictive maintenance has been attracting attention due to the development of the Internet of Things (IoT) and Artificial Intelligence (AI).

On the other hand, KYB's equipment maintenance methods focus on breakdown maintenance and preventive maintenance. In the former case, equipment failure causes a drop in productivity and product defects, and in the latter case, excessive maintenance increases maintenance costs.

To solve these problems, we have developed an equipment predictive maintenance system. This system utilizes the latest technologies, including IoT, AI, and cloud computing, to build a system with functions such as data collection, storage, failure prediction, and visualization and the system is now in operation at a practical level. This paper describes the basic functions developed to realize predictive maintenance, and the operation management mechanisms and features that have been developed for global deployment.

1 Introduction

The Internet of Things (IoT) and Artificial Intelligence (AI) have advanced dramatically in recent years and attracted the attention of not only academia and the IT industry but also a variety of other fields including medical and manufacturing.

The manufacturing industry has made use of IoT and AI to "detect faulty parts," "predict equipment failure" and "optimize production plans," which has made it possible to achieve these activities with higher accuracy.

In terms of equipment failure prediction, we are now finally seeing the possibility of implementing "predictive maintenance," which refers to a maintenance system based on the automatic monitoring of equipment status to provide a prediction of failure occurrences, enabling maintenance personnel to carry out maintenance when a sign of failure is detected. Under predictive maintenance, maintenance can be carried out in a timely manner, preventing occurrences of failures as well as maximizing the usage of parts. Thus, predictive maintenance will hopefully minimize maintenance costs.

On the other hand, the equipment maintenance system in actual practice by KYB focuses on "breakdown maintenance," which only requires personnel to conduct maintenance after failure, and "preventive maintenance," which requires personnel to conduct maintenance periodically or after a certain period of operation. In the former case, equipment failure causes productivity losses and product defects. In the latter, excessive maintenance may increase maintenance costs.

To solve these problems, we have developed a predictive equipment maintenance system. This system utilizes the latest technologies, including IoT, AI, and cloud computing, to build a system with functions such as data collection, data storage, failure prediction, and visualization, and the system is now in operation at a practical level.

2 Requirements

The following lists the requirements for implementing a equipment predictive maintenance system and putting it into operation:

① An environment for continuously accumulating and analyzing data collected from equipment must be available.

② The system must be able to provide not only normal/abnormal judgement but also numerical assessment of failure risk.

③ The system must be able to predict a failure at least two weeks before its occurrence Note 1), rather than immediately before the occurrence.

④ The current status of equipment must be visualized and available even to personnel in an office.

⑤ The system must be designed for general purpose to be applied to different types of equipment, not to a specific one.

⑥ The system must be able to be deployed on a global basis.

Note 1) This period has been determined with consideration given to how long it generally takes to get ready for maintenance (part arrangement and personnel allocation) after prediction of a failure. In reality, the period depends on the equipment.

3 System Overview

3.1 System Architecture

To realize predictive maintenance, it is necessary to collect data for determining the status of equipment. Data items to be collected and the collection methods depend on the target equipment and/or the failures to be detected. One of the typical data items is "vibration." Vibration data is usually collected at a high sampling rate (for example, 10 kHz or more), resulting in large amounts of data. On the other hand, it may be sufficient for some types of equipment to collect data at a low sampling rate (for example, about 1 Hz), which generates small amounts of data. Therefore, in order to achieve global deployment of a general-purpose system applicable to many different types of equipment, the system must be designed to be able to handle small amounts of data at a lower cost while having sufficient capacity to deal with a surge of data, if any.

This means that the storage capacity and processing capability should be able to be scaled up/down according to the data volume to be handled and processed. However, the conventional on-premises[Note 2)] system was incapable of achieving such scaling, so in this development project, we established KYB's own platform on the Amazon Web Services (AWS) public cloud.

Fig. 1 shows a block diagram of the system we developed.

The platform can provide various serverless[Note 3)] services to deal with most tasks related to predictive maintenance except for a few tasks. The processing performance and its associated costs can be charged by a subscription system under which users only pay for "as much as they use." KYB can also cope with the service flexibly depending on the scale of equipment.

Note 2) "On-premises" means that the software system is installed on computers on the premises of the organization using the software.

Note 3) "Serverless" is an idea that the organization builds a software system by using managed services controlled by a public cloud service provider such as AWS and dynamically setting necessary resources for processing, instead of having its own server by itself.

3.2 Collection of Equipment Data

We built a data collection system that periodically captures data from sensors installed to determine the status of target equipment and stores the data in files in an FA computer. These files are periodically uploaded to AWS.

To illustrate this, the following introduces a case of data collection from an overhead trolley conveyor for product transfer. Photo 1 shows the drive motor for the conveyor and its peripheral components. An acceleration sensor is installed in the drive of the transport chain (bottom left corner of Photo 1). Photo 2 is an enlarged view of the area where the acceleration sensor is installed. This installation

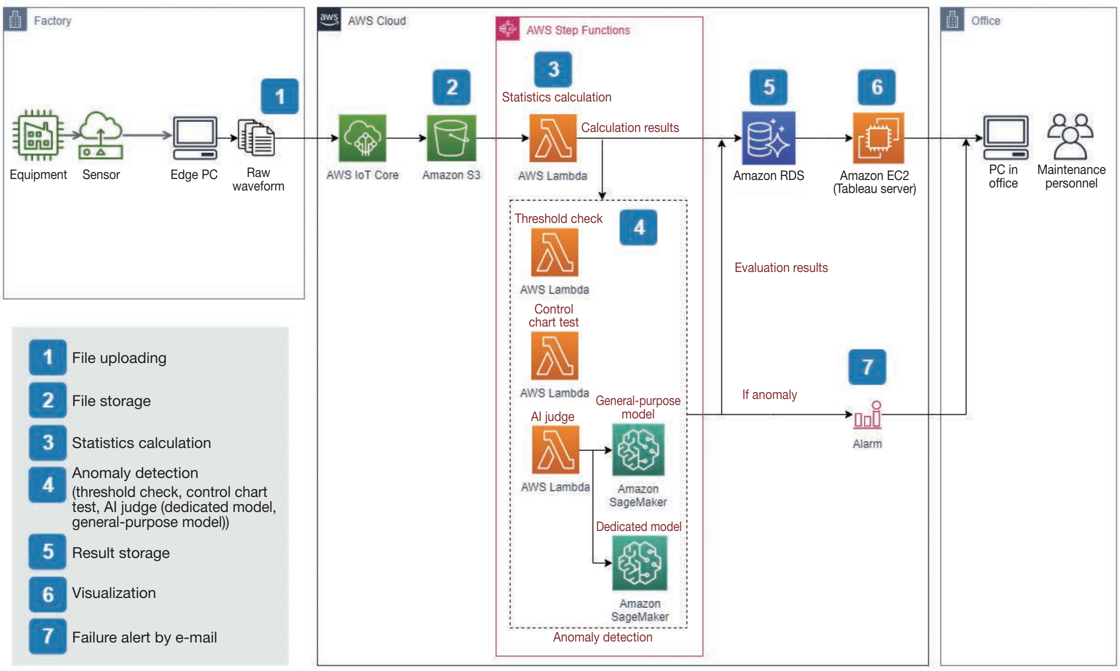


Fig. 1 System Architecture Diagram (overview)

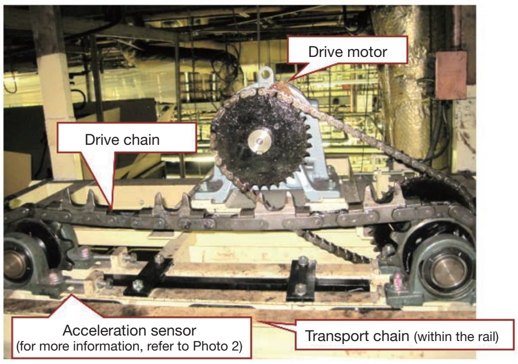


Photo 1 Conveyor equipment

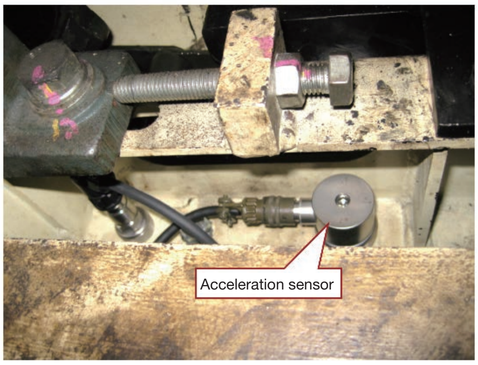


Photo 2 Area with acceleration sensor

is intended to predict conveyor failures during transport by measuring the vibration of the drive.

Predictive maintenance focuses on the detection of status changes caused by wear or other anomaly of equipment from a long-term point of view and does not cover sporadic failures. In other words, data should not necessarily be collected all the time. Periodic collection, for example, "collect data only for 10 seconds every hour" may be sufficient. We then developed an application program that collects data for a certain period of time at regular intervals and outputs files, as part of this development project. It should be noted that we designed the data collection system to output files of collected data before uploading so that the system can generally be applied to many different types of equipment including PLC [Note 4].

For data uploading, AWS IoT Core [Note 5] and AWS STS [Note 6] services are used to implement the uploading of files of collected data to AWS and the uploaded data is finally stored in Amazon S3, which is a storage service of AWS. By using these services, only devices registered on AWS are allowed to upload data securely using temporary authentication information.

Note 4) Programmable Logic Controller: a control device that was developed as an alternative to relay circuits

Note 5) A service that makes various AWS services available to IoT devices

Note 6) AWS Security Token Service: a service to provide temporary security authentication to permit access to AWS resources

3.3 Equipment Failure Prediction Function

3.3.1 Overview of Function

To implement a predictive maintenance system in this development project, we used machine learning to develop a failure prediction function. For judging the equipment status between normal and abnormal (failure) as in this case, "supervised learning" and "unsupervised learning" techniques are generally available. We selected the unsupervised learning technique because it was difficult to obtain large amounts of anomaly (failure) data as required by the supervised learning technique. We only used "normal" data for learning, according to the concept of anomaly detection that tries to detect deviations from the "normal" data set.

For machine learning, we created two types of models based on different concepts: "a dedicated model" and "a general-purpose model."

Table 1 shows a matrix of these two models:

Table 1 Comparison of models

	Dedicated model	General-purpose model
Available for	Several months	1 week
Accuracy	High	Middle [Note 7]
Algorithm	Any	Statistical machine learning
Feature	Any	Statistics-based
Learning	Manual	Automatic
Prediction	Automatic	Automatic

Note 7) The accuracy is lower than for the dedicated model, but higher than for the conventional threshold check.

The dedicated model is a machine learning model specifically designed for a specific equipment unit. In general, machine learning seldom produces ideal results only with data input. Fine tuning such as extraction of appropriate features, selection of learning techniques or parameter setting may contribute to more accurate results in many cases. For an equipment unit requiring high accuracy, a dedicated model specific to the unit is created. However, creating a dedicated model entails a problem in that it takes a longer time to be completed due to the fine tuning. In a case that a dedicated model was created for an equipment unit, it took several months to complete the model creation, including data collection.

On the other hand, the general-purpose model is designed to be able to be generally applied to any equipment unit, not a specific one. A general-purpose model is created by the statistical machine learning technique that uses features mainly for statistics, including the average of a set of normal data for around one week, [Note 8] and then detects deviations from the normal data set. That is, the general-purpose model enables simplified anomaly detection only with a simple method. The accuracy is certainly lower than for the dedicated model, but it may be sufficient depending on the equipment. It is also possible for us to operate the system based on a general-purpose model that can be quickly adapted in the early stage after its introduction, and to switch to a dedicated model as soon as it is completed. In this way, the failure prediction function we developed can offer both quick deployment and high accuracy with these two types of models.

Note 8) The period can be freely adjusted.

3.3.2 Cases of Development

As an example of the learning methods we devised for the development of dedicated models for given equipment, this section introduces Spec Masked Autoencoder. This method uses Autoencoder (hereinafter "AE"), which is one of the deep learning methods. AE was originally used for dimensionality reduction or feature extraction and is recently used for data creation, clustering or anomaly detection. The method we developed adopted the concept of anomaly detection. Fig. 2 shows the learning flow of these methods.

The general AE carries out encoding and decoding for machine learning so that the input data is identical to the output data. For Spec Masked AE, a mask is added to hide part of the input information and then removed to expose the output data. Machine learning is conducted so that the output data is identical to the original input data [1]. The mask addition and removal process is added in this way to intentionally make the issue more difficult to suppress overlearning [Note 9], with an aim at developing a flexible model.

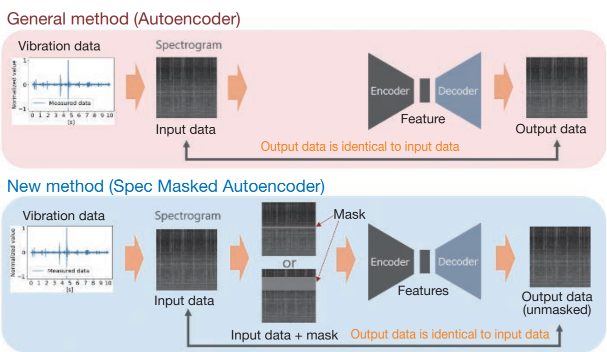


Fig. 2 Learning flow of AE and Spec Masked AE

Note 9) Overlearning refers to adapting to learning data too much to become unable to adapt to unknown data.

3.3.3 Operation and Management of Machine Learning Models

For a software system using machine learning, model development is just the beginning. It is needed to develop a scheme to properly manage the entire system to allow continual operation. For example, if the conventional trend of data collection changes due to seasonal variation or a change in the processing conditions of the equipment, the system may no longer yield proper judgement with the existing model. In this case, the model should be updated by relearning. During the updating, the model evaluation, version control and distribution method must be clear. An unexpected error may otherwise occur.

In this development project, we effectively used AmazonSageMaker [Note 10] and AWS Step Functions [Note 11], both of which are AWS services, to implement model management and develop a learning and prediction workflow. For model management, for instance, the model is tagged to indicate whether the model is for development or for actual use and just changing the tag of the model for development, for example, will switch the model over to actual use. For the general-purpose model, learning, distribution and prediction processes have been automated so that a model can be automatically created to allow prediction to be started as soon as a set of data has been collected for a specified period of time.

Note 10) A service to provide an environment where machine learning models can be quickly developed, learned and distributed.

Note 11) A service that allocates two or more AWS services to create a series of workflow.

3.4 Visualization of Equipment Status

To visualize the status of equipment, we developed a view using Tableau, which is one of the BI tools [Note 12].

Note 12) Business Intelligence tool: A tool to collect, analyze and visualize large amounts of data accumulated in an organization, thereby helping the organization to make decisions quickly.

3.4.1 Equipment Anomaly Information View

Fig. 3 shows the view displaying equipment units with anomalies, and the distribution and changes of their failure risks [Note 13) Note 14)]. This view is basically displayed as a main screen all the time. On this screen, the user can identify the equipment units with anomalies or high failure risks and then take actions as follows:

- Check equipment data (statistics).
- Go and see the actual equipment.
- Develop a maintenance plan for repair.

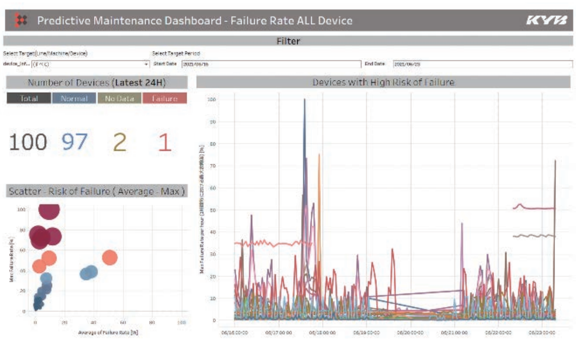


Fig. 3 Equipment anomaly information view

Note 13) Numerically indicates the extent to which the equipment is likely to have a failure.

Note 14) Data shown in the view is only sample data and different from the actual data.

3.4.2 Specific Equipment Statistics View

Fig. 4 shows the view displaying changes and variation of statistics (such as average and standard deviation) of data collected from a given equipment unit [Note 15]. If the equipment unit is found to have an anomaly or a high failure risk, the user can open this view to see how the actual statistics of the equipment unit have changed. It is expected that the user can specifically determine the anomaly.

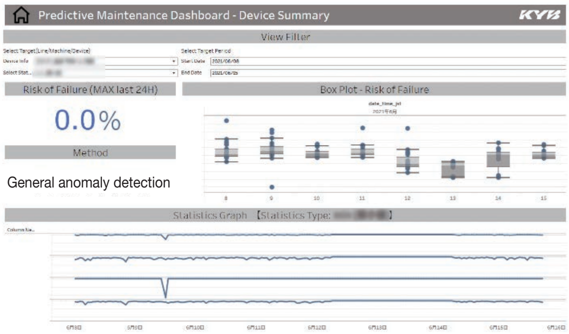


Fig. 4 Specific equipment statistics view

Note 15) The part with confidential information has been intentionally deleted or shaded.

3.4.3 Multiple Equipment Statistics Comparison View

Fig. 5 shows the view displaying changes in statistics of data collected from two or more equipment units Note 16). If any one of the equipment units is found to have abnormal changes in statistics, the user can open this view to compare the unit with another under the same conditions or monitored with the same data items side by side. It is expected that the user can identify the location of the anomaly.

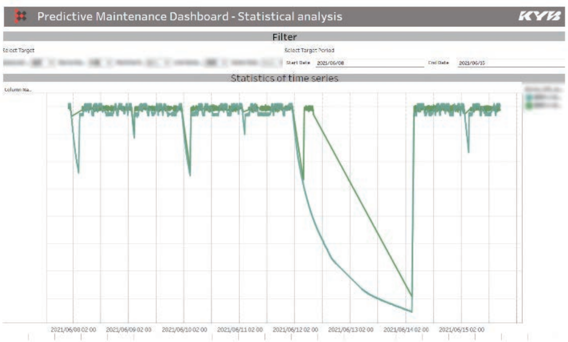


Fig. 5 Multiple equipment statistics comparison view

Note 16) The part with confidential information has been intentionally deleted or shaded.

4 Cases of Equipment Failure Prediction

This chapter introduces cases of equipment failure prediction using the dedicated or general-purpose model we have developed.

4.1 Equipment Failure Prediction with Dedicated Model

A case of equipment failure prediction using a dedicated model is shown in Fig. 6. In this case, a failure actually occurred before the system was put into operation (i.e., data collection was already started but no model had been created). A dedicated model was created thereafter and used to provide retrospective failure prediction against the past failure as shown in the figure Note 17). In Fig. 6, the X-axis indicates time covering nearly five months while the Y-axis indicates the failure risk output by the machine learning model. The first red dotted line shows the date on which the failure occurred and when a temporary remedy was administered. The second red dotted line indicates the date on which the major affected parts were replaced. Consequently, if a threshold level according to the failure risk output by the machine learning model had been set as indicated by the horizontal dotted line in the figure, the failure could have been predicted about one month before the occurrence. In fact, the failure risk decreased after a temporary remedy was administered but remained at high levels to some extent and tended to dramatically drop after the replacement of major parts. Therefore, the prediction curve can be said to represent ideal results in accordance with the actual status of equipment.

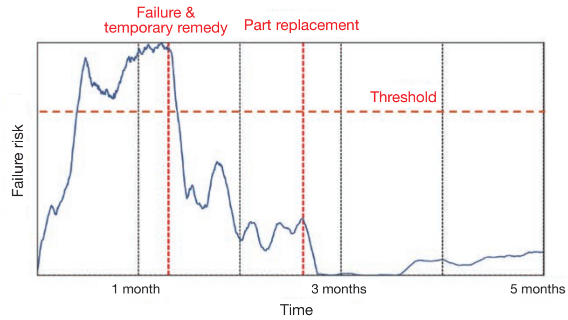


Fig. 6 Retrospective failure prediction for a past failure

Note 17) Specific numbers have been intentionally deleted or shaded as they are confidential information.

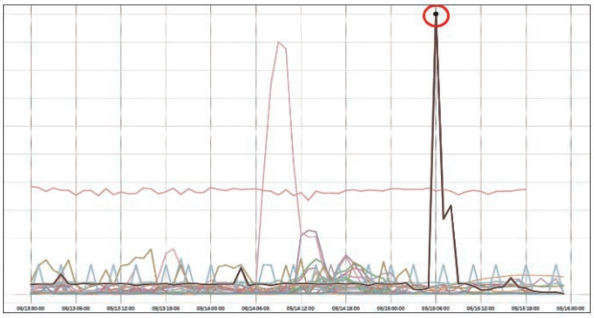
4.2 Equipment Failure Prediction with General-purpose Model

Cases of equipment failure prediction using a general-purpose model are shown in Figs. 7 and 8. These figures show the failure risk proposed by the system during anomaly detection and changes in actually collected data (temperature in these cases) Note 18). In both the figures, the X-axis indicates time while the Y-axis indicates failure risk for diagram (a) and temperature for diagram (b). The area enclosed by a red circle indicates anomalies detected by the system.

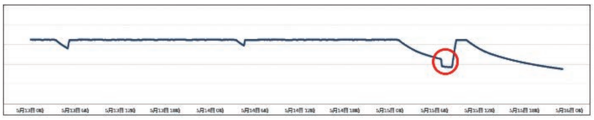
Fig. 7 shows a case of anomaly detection with a sudden fall of temperature. For the equipment, which normally experiences moderate decreases in temperature with natural cooling, the temperature suddenly dropped to raise the failure risk dramatically. In fact, the sudden drop in temperature was caused by equipment maintenance, not an equipment failure. Nevertheless, the system successfully detected a unusual point of change.

Fig. 8 shows a case of anomaly detection with fluctuations in temperature. For the equipment, which is normally exposed to almost constant temperature or moderate increases or decreases, the temperature repeatedly fluctuated in a short time to raise the failure risk dramatically. In fact, the fluctuations in temperature were caused by repeated start-ups and interruptions of the equipment for the purpose of tool changes and commissioning, not an equipment failure. Nevertheless, the system successfully detected a point of change different from the norm in this case as well.

The cases above indicate that it is possible to detect equipment anomalies by using a general-purpose model, even for changes that can hardly be detected with simple threshold evaluation.

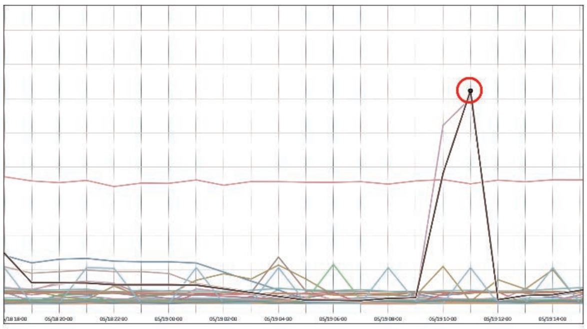


(a) Changes in failure risk

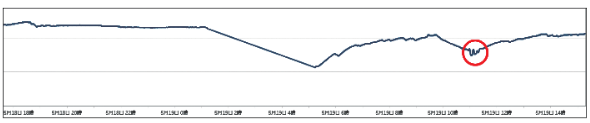


(b) Actual temperature changes

Fig. 7 Anomaly detection with sudden fall of temperature



(a) Changes in failure risk



(b) Actual temperature changes

Fig. 8 Anomaly detection with irregular changes in temperature

Note 18) Specific numbers have been intentionally deleted or shaded as they are confidential information.

5 Efforts Toward Global Deployment

As shown in Fig. 1, this new system relies on the cloud environment to provide a platform for a series of failure prediction from data analysis to visualization. Thus, the system can be expected to be deployed more swiftly than the conventional counterpart. To realize stable system operation while making use of the advantage, however, it is necessary to satisfy the following requirements:

① The operating status of the system must be able to be monitored.

② The operation rule of the system must be clarified.

This chapter describes how we have met these requirements:

5.1 Development of System Monitoring Function

To ensure that the operating status of the system can be determined anywhere, we implemented system status visualization and notification functions in the system by putting the Datadog server monitoring tool to full use. Fig. 9 shows a block diagram of some of the system monitoring functions. The function is designed to transfer all security and system log data to Datadog for batch control and to notify any anomaly to a chat tool (Microsoft Teams), thereby enabling an administrator to promptly initiate remediation.

What is to be monitored by the system can be roughly divided into:

① security

② system.

The following sections specifically describe each of these.

5.1.1 Security Monitoring

The security monitoring here refers to the monitoring of whether the secure environment is maintained. For example, is there any room for the system to allow outsiders to invade? Is there any risk of data leakage? Can the system detect any attack? Although it is a precondition to establish secure security in the design stage, it is not unreasonable to assume that the system may be attacked by an external entity as long as it is connected to the Internet. Therefore, we built an environment to provide continual security monitoring. The following introduces some of these established security monitoring functions.

In this new system, Amazon GuardDuty (hereinafter "GuardDuty") is enabled to detect any illegal login, activ-

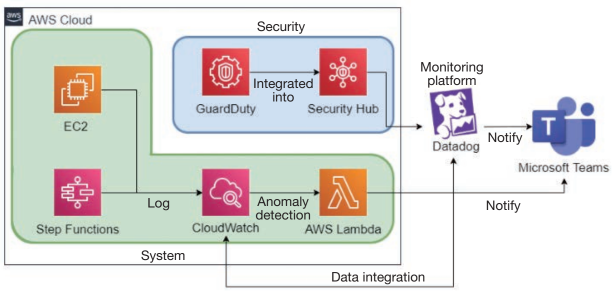


Fig. 9 Block diagram of system monitoring function

ity or communication to AWS. GuardDuty is a fully managed thread detection service that continuously monitors AWS accounts for malicious activity or illegal operation. It collects and monitors logs of accounts used to operate AWS and of IP addresses connected to AWS all the time, thereby enabling detection of illegal accesses and activities.

The system also uses AWS Security Hub (hereinafter "Security Hub") to generally verify total security. Security Hub is a service that collects and manages all security-related information on AWS. Information about GuardDuty stated above is also collected by Security Hub. In the case of an anomaly, the anomaly information, including the time of occurrence, description of the anomaly, and location of the anomaly, is notified as shown in Fig. 10 Note 19) so that the user can promptly cope with security vulnerability.

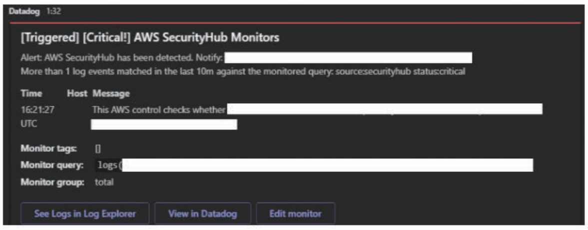


Fig. 10 Notification

Note 19) Values and logs related to the system are not disclosed.

5.1.2 System Monitoring

The system monitoring function monitors the system operation for stability, for example, whether the system is operating properly or whether the system can easily cope with an anomaly, if any. This new system uses Amazon CloudWatch Note 20) (hereinafter "CloudWatch") for total system monitoring to collect metrics and logs. The collected metrics and logs are visualized by Datadog.

Part of the Datadog dashboard is shown in Fig. 11 Note 21).

Fig. 11 shows a dashboard that centrally controls metrics and logs of services implemented. The user can grasp the situation by identifying, for example, which process has failed and what caused the failure.

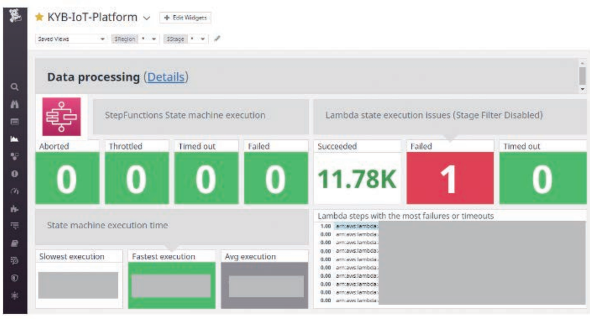


Fig. 11 Datadog dashboard

Note 20) A service that collects metrics and logs of AWS resources and applications

Note 21) Values and logs related to the system are not disclosed.

5.2 Clarification of Operation Rules with IaC

When building this system, we adopted the concept of Infrastructure as Code (hereinafter "IaC") to secure superior deployment and improved maintainability.

IaC is the process of managing infrastructure configuration with code. The server environment and application settings, which have conventionally been configured manually, are all coded. This means that there is no procedure for manual configuration. Instead, the user creates configuration management files that describe environments to be built with code. Fig. 12 shows the difference between IaC and conventional operation. Major benefits of IaC include fewer human errors due to reduced manual operation, easier version control thanks to coded files, and automated operation from test to implementation with CI/CD Note 22).

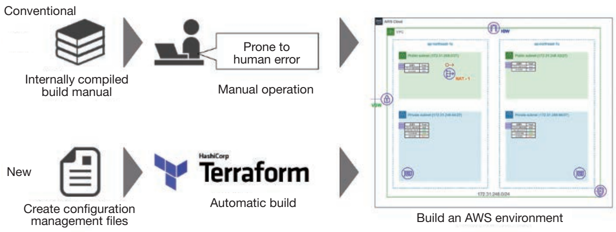


Fig. 12 Difference between IaC and conventional build

In this new system, infrastructure creation has been automated by linking the existing GitLab version control tool with HashiCorp's Terraform, which is one of the IaCs, providing an environment that enables control of differences. If another site is to introduce the equipment prediction system, it is possible to build another same environment instantly for the site. Fig. 13 shows this automated flow of infrastructure creation. In Fig. 13, the steps ① and ② correspond to existing processes of preparation of instruction manuals, discussion of specifications, and version control. The introduction of IaC eliminates the need for controlling instruction manuals and only requires the appropriate site to discuss specifications. The next step ③ shows automated testing of configuration management files. Individual test jobs are carried out before their files are merged Note 23) into GitLab. Should a job not be cleared, the system issues an error and does not allow the files to be merged into GitLab.

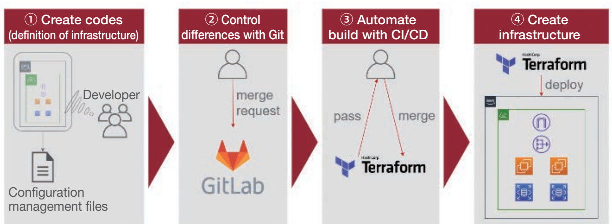


Fig. 13 Flow of infrastructure creation with IaC

Note 22) A system that automates the build, test and development processes. Stands for Continuous Integration and Continuous Delivery.

Note 23) Refers to the process of integrating edited contents into their original files.

6 Future Prospects

This new system makes it possible to predict equipment failures and to also provide an environment that allows us to become aware of something new when we access the visualized status information of our equipment.

To efficiently promote lateral deployment of this system, it is indispensable for us to cooperate with other sites. While discussing the issues on the target equipment with the related sites, we will steadily promote the introduction of the new system, providing an environment where we can identify the status of all equipment units wherever we are, whether home or abroad.

For even more meaningful analysis, we have worked on this system for potential linkage with various other systems. The most recent example is that we have discussed possible linkage between data of remedies actually administered during equipment maintenance and the equipment's vibration/temperature measurement data collected for the system. If this is achieved, it can be expected to widen the data utilization, including verification of the effects of the remedies and analysis of similar cases. However, data linkage poses a challenge that the data is available in text format, not numerical. To tackle this challenge, we are considering applying AI to text analysis to achieve a more advanced analysis.

Our final goal is to build an expanded company-wide, cross-functional IoT-Platform based on information linkage with Production and Quality Management, contributing to higher productivity and improved quality.

7 Concluding Remarks

This new system has realized predictive maintenance and real-time equipment monitoring that were difficult to be achieved before. With predictive maintenance, maintenance cost reductions are expected. We would like to not only apply the system to equipment maintenance alone but also establish linkage between the system and various other systems to implement even higher analysis functions and add greater value.

Finally, we would like to take this opportunity to sincerely thank those concerned from related functions who gave us their great support and cooperation for this development.

References

1) Ayaka MATSUI, Shota ASAHI, Satoshi TAMURA, Satoru HAYAMIZU, Ryosuke ISASHI, Akira FURUKAWA, Takayoshi NAITOU: Anomaly detection in mechanical vibration using combination of signal processing and autoencoder, NCSP'20, 2020.

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Product Introduction

Development of Cylinder Equipment for Mining Dump Trucks

TANIGAWA Natsuki, HASEGAWA Kazuki

1 Introduction

1.1 Overview

Mining dump trucks (hereinafter "mining trucks") are off-highway vehicles specifically engineered for use in mining sites such as mines and quarries. They also serve as construction machinery to transport coal, iron ore and soil & rock excavated with their mining excavator (Photos 1 and 2). In many cases, their bodies undergo periodic maintenance. If a mining truck still becomes inoperable due to a failure or some other reason, this directly leads to profit loss for the mine operator. Thus, mining trucks are required to have extremely high durability.

Photo 1 A mining truck loading
(Reprinted from Hitachi Construction Machinery's website)

Photo 2 Appearance of EH5000AC-3 from Hitachi Construction Machinery
(Reprinted from Hitachi Construction Machinery's website)

Table 1 shows the general specifications of EH5000AC-3 from Hitachi Construction Machinery.

Table 1 General specifications of EH5000AC-3 from Hitachi Construction Machinery

Nominal payload	kg	296,000
Operating weight (complete vehicle curb mass)	kg	204,000
Total vehicle weight	kg	500,000
Body capacity (heap/struck)	m^2	202 / 148
Maximum travel speed	km/h	56
Tire size		53/80R63

A mining truck can transport loads weighing more than its own body weight. A typical large type is shown in Photo 2. This huge vehicle body can have a total weight of 300 to 500 tons when fully loaded. To bear the weight, the truck is equipped with another two tires with diameter of not less than 2 meters on the front and two tires of the same size on the right and left wheels of the rear axis, respectively (Photo 3).

Photo 3 Rear wheels of mining truck
(Hitachi Construction Machinery's booth at MINExpo® 2016)

In mines where these mining trucks are used, a mining excavator generally operates with two or more mining trucks. This means that the market size for mining trucks is larger than that for mining excavators. Although KYB has designed and produced cylinders for use in mining excavators for a long time, it is the first time for the company to enter the market of mining trucks with this cylinder equipment.

1.2 Cylinder Equipment for Mining Trucks

A mining truck is equipped with suspension cylinders as hydraulic shock absorbers, as shown in Fig. 1 (① Front: Photo 4, ② Rear: Photo 5), and a hoist cylinder as a hydraulic direct-acting actuator on the right and left sides of the vehicle, respectively (Photo 6).

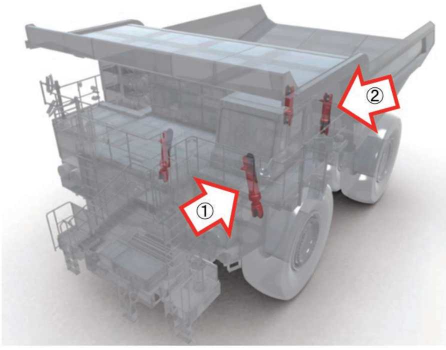

Fig. 1 Suspension cylinders

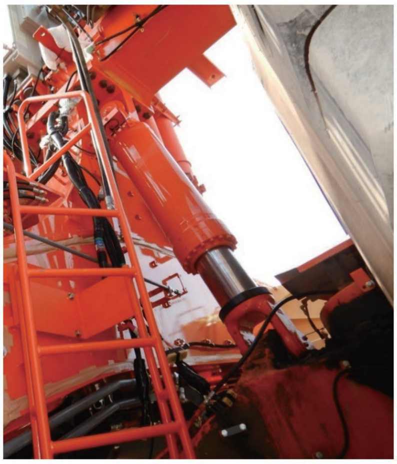

Photo 4 ① Front suspension cylinder

Photo 5 ② Rear suspension cylinder

1.3 Target trucks

In this development project, we developed front and rear suspension cylinders and hoist cylinders for use on Hitachi Construction Machinery's EH5000AC-3 mining truck. The following provides information about these products, including their structures, along with the background of the development.

Photo 6 Hoist cylinders

2 Background of Development

2.1 Required Functions of Cylinders

Suspension cylinders are shock-absorbing equipment with two major functions. One is the function to hold the vehicle body, which supports the weight of the vehicle, absorbs the impact from the road surface, reduces the load applied to the vehicle frame, and prevents the load from collapsing. The other is the function to damp vibration, which converts the vibration energy of the vehicle body into heat to ensure stable operation of the vehicle with minimum vibration. For general automobile suspensions, the vehicle-holding function is implemented by coil or air springs, while the damping function is implemented by shock absorbers. For mining truck suspensions, the vehicle-holding and damping functions are both implemented in the same pressure vessel.

The hoist cylinders are used to raise and lower the load-carrying body to unload soil and rock piled thereon. A telescopic type is popularly used to sufficiently cover the required stroke that is usually very long to reach the unloading position.

2.2 Suspension Cylinders

As described above, a suspension cylinder is a hydraulic shock absorber that can deliver both vehicle-body-holding and vibration-damping functions in the same pressure vessel. The suspension cylinder can deliver the body-holding function by the compressibility of a gas and a hydraulic fluid filled in the cylinder itself and the vibration-damping function by an orifice installed between oil chambers. This mechanism uses the same principle as that of the hydra-pneumatic shock strut for aircrafts (hereinafter “oleo strut”) invented in 1924 by Shiro Kayaba, who founded KYB.

Although it is the first time for KYB to enter the market for suspension cylinders for mining trucks, we brought together again the engineering techniques for various hydraulic shock absorbers for automobiles, railways and aircrafts that had been evolved from the oleo struts. Furthermore, we combined these techniques with the engineering techniques for hydraulic cylinders for construction machinery for the purpose of development.

2.3 Hoist Cylinders

In terms of double-acting, telescopic hydraulic cylinders that can be used to raise and lower the decks of mining trucks, KYB's existing portfolio already included a cylinder for special vehicles with payload of not more than 2 tons. The target EH5000AC-3 mining truck has a payload of as much as about 300 tons. To provide the superlatively higher thrust needed to lift the mining truck's body, a large-sized hoist cylinder is needed. KYB had not designed or produced such a long, large-sized telescopic cylinder. We therefore decided to develop a dedicated cylinder for mining trucks based on the existing hoist cylinder for special vehicles.

3 Product Specifications

3.1 Use Environment and Applications

Because mining trucks are used in mines throughout the world, consideration should be given to a variety of use environments, including hot and humid, cold climate and dusty conditions. In addition to the assumed environment temperature range of -40 to 50 ˚C, it must be assumed that mining trucks will be used in harsh environments. For example, they run on unpaved surfaces in mines, during which the built-in cylinder equipment is exposed to sand and dust that may become dry and be adhered on the surface of the rod or may freeze at low temperatures. In comparison to cylinders for mining excavators that are used in mines as well, those for mining trucks are exposed to more sand or dust because the trucks travel longer distances. This means that the application involves harsh environments where dust may enter the cylinder through the sliding parts of the piston rod.

Many of the components used in mining machinery undergo periodic overhaul and repair for long-term use. The suspension and hoist cylinders we developed in this project are also applicable to the usage and are required to have long-term durability, particularly in their high-strength parts, such that the structure will not fail after the replacement of consumables, including seals and sliding parts, or even after repeated overhauls.

3.2 Basic Specifications of Suspension Cylinders

- External dimensions of cylinder: Fig. 2
- Maximum pressure: 60 MPa
- Hydraulic fluid temperature range: -40 ˚C to 90 ˚C
- Prefilled hydraulic fluid: Silicone synthetic oil

In the suspension cylinder, a hydraulic fluid and a gas are filled in the same space (Fig. 3) to deliver the vehicle-body-holding function. The cylinder is installed onto the vehicle body in a position such that its rod is located on the bottom, causing the gas to occupy the top section of the cylinder tube. When the suspension cylinder retracts, the internal volume of the cylinder decreases by as much as the rod invades, thereby compressing the gas and hydraulic fluid to raise the cylinder's internal pressure. When gas is used as a spring, the pressure increases as the cylinder retracts according to Boyle's law, showing non-linear gain spring characteristics. The gain spring characteristics with gas compression are beneficial to ensure both the riding comfort of a vehicle with empty load involving a low spring constant and high-load support of the fully loaded vehicle involving a gain spring constant. The gas spring system can thus be optimally used in mining trucks with big differences in loads between the empty and loaded states of the vehicle.

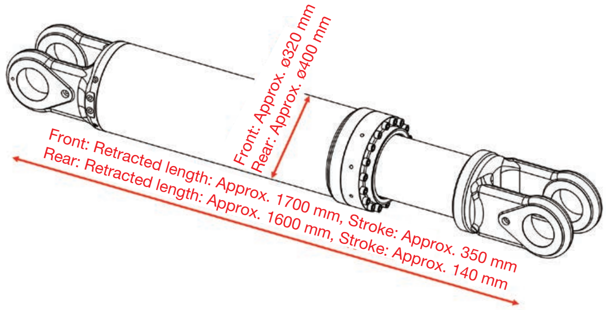

Fig. 2 Appearance of suspension cylinder

The suspension cylinders of a mining truck have to be installed in a limited space, delivering a limited length of strokes. Just the four suspension cylinders have to support the total weight of the vehicle body as heavy as 500 tons. The maximum dynamic pressures can reach as high as 60 MPa. This maximum pressure of the suspension cylinders of a mining truck is substantially higher than the main relief pressure of about 30 MPa of the hydraulic circuit of a mining excavator.

The suspension cylinders for Hitachi Construction Machinery's mining trucks use silicone synthetic oil as hydraulic fluid. In addition to the gain spring characteristics with gas compression, the spring characteristics with hydraulic fluid compression will also be used in the high-load (high-pressure) zone where the gas might apparently no longer exist in the cylinder. The use of silicone synthetic oil, whose bulk modulus is higher (more compressive) than that of the mineral oil used for general hydraulic shock absorbers, helps maintain the spring constant at a lower level than that for mineral oil even in the high-load (high-pressure) zone, making it possible to reduce the load applied to the vehicle frame.

To offer the vehicle vibration damping that is the other important function, an orifice has been constructed in the piston rod section filled with hydraulic fluid. As the suspension extends and retracts to cause the hydraulic fluid to flow through the orifice with a resistance, there will be a difference in pressure between the top and bottom chambers, generating a damping force. Adjusting the diameter of the orifice and the geometry of the oil passage will attain the desired damping force characteristics.

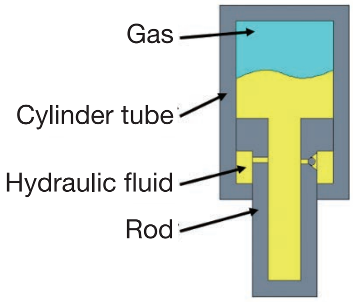

Fig. 3 Overview of suspension cylinder

3.3 Basic Specifications of Hoist Cylinders

- External dimensions of cylinder: Fig. 4
- Type of cylinder: Double-acting, 3-stage telescopic type
- Pressure rating: 21 MPa
- Hydraulic fluid temperature range: -40 ˚C to 90 ˚C

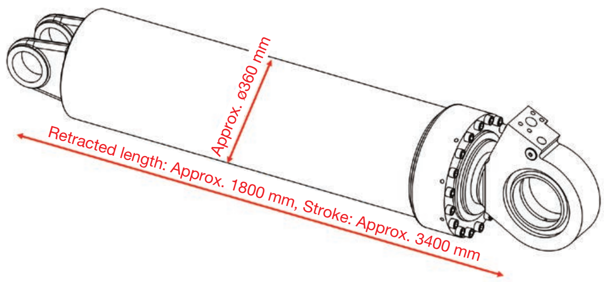

Fig. 4 Appearance of hoist cylinder

As shown in Fig. 5, the hoist cylinder consists of a bottom chamber and a rod chamber with telescopic multiple rod sections, of which the smallest rod section has internal piping. When the cylinder extends to lift the body, the pressurized fluid enters the extension port to flow into the bottom chamber through the internal piping, causing the rod sections to sequentially extend. When the cylinder retracts to bring the body down, normally the rod sections retract sequentially from the smallest one by the body's own weight. Because of the double-acting feature, if the cylinder cannot easily retract by the body's own weight due to the dense hydraulic fluid at a lower temperature, the fluid can enter the retraction port applied with a higher pressure to flow through the rod sections to fill the rod chamber, thereby providing the capability of forcefully retracting the cylinder.

4 Development Challenges and Design Considerations

4.1 Suspension Cylinders

4.1.1 Establishment of Holding and Damping Force Characteristics Calculation Models

As described above, the suspension cylinder is required

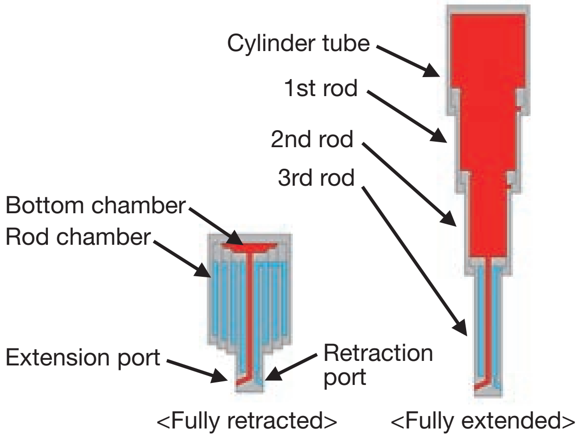

Fig. 5 Overview of hoist cylinder

to deliver vehicle-holding and vibration-damping functions. KYB has techniques to calculate the holding and damping force characteristics of hydraulic dampers when mounted on automobiles or railway vehicles, as well as vehicle behavior simulation technology. For suspension cylinders for mining trucks, however, theoretical calculation alone was insufficient to determine the effect of the fluid compression and gas dissolvement on the characteristics. The fluid compression and gas dissolvement depend on the type of fluid and gas used or the combination of the two. Therefore, a basic test needs to be conducted using a servo testing machine to measure the holding and damping force characteristics, which will be compared to the theoretical calculations to determine the difference. Then, appropriate correction must be made.

For the vibration testing of suspension cylinders for mining trucks, an actual machine or a large-scale testing system with a thrust and an exciting speed equivalent to those of the actual machine needs to be available. However, a verification test using such an actual machine or large testing system would entail a higher development cost and a longer development period. In this development project, a miniature suspension of such a size that can be vibrated with the existing servo testing machine was fabricated and subjected to the basic test (Photo 7).

In the basic test on the miniature suspension, the effect

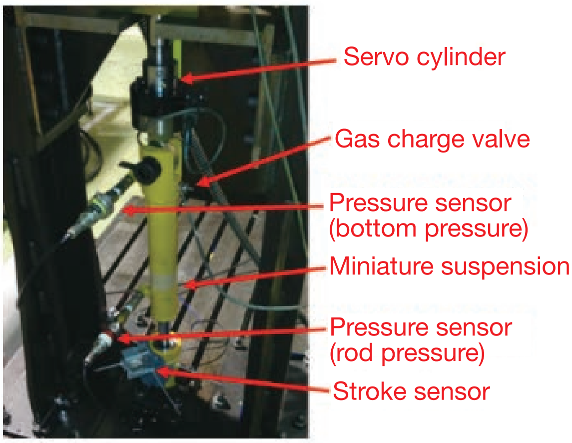

Photo 7 Miniature suspension

of the fluid compression and gas dissolvement on the holding and damping force characteristics were determined, from which an appropriate correction factor to add to the theoretical calculations was set. Furthermore, a dynamic characteristics analysis model of the suspension cylinder body and a simulation model of the vehicle body with these characteristics taken into account were created. These models make it possible to verify the effect of the suspension characteristics on the vehicle motion before installation on the actual vehicle.

4.1.2 Pressure Durability of Structure

As mentioned above, the suspension cylinder is a pressure vessel repeatedly subjected to high pressure and is also a damper subjected to repeated overhauls for long-term use. To enhance the pressure durability of a structure, it may be usually considered to make its high-strength parts thicker. For suspensions, however, their weight increase gives rise to several disadvantages, including deteriorated vehicle movement due to the heavier unsprung mass and a reduced payload resulting from the higher vehicle weight. It is thus essential to achieve optimal design with a good balance between durability and weight.

For this development project, Hitachi Construction Machinery provided us with the pressure data of suspension cylinders that were in actual operation in harsh environments. Based on KYB’s own expertise in frequency analysis accumulated in the design of high-pressure cylinders for hydraulic excavators, KYB clarified the required level of durability of the cylinders to satisfy the specified service life of the vehicle. As the durability demanded by the market has become obvious, KYB has successfully designed a cylinder that has the required level of durability and has a minimum weight based on the company's expertise in fatigue design of pressure vessels.

4.1.3 Strength against External Force

Suspensions for mining trucks need to control the cylinder stroke at the extension and retraction ends. Mining trucks, which frequently travel over bad roads, may have their tires floating up from the road surface or have their suspension cylinders extending far up to the extension end. It is needed to assume that a large external tensile force may be applied. By making use of KYB’s engineering expertise related to the fastening and clevis sections of cylinders applied with a high external force at the stroke end accumulated in the design of high-pressure cylinders for hydraulic excavators, KYB achieved a design meeting the breaking strength and durability requirements.

4.1.4 Selection of Oil Seals

Oil seals used in suspension cylinders must maintain their elasticity even at -40 ˚C, which is the lower limit of the service temperature range, and they must be able to accommodate the temperature increase of the hydraulic fluid. In addition, their resistance to silicone synthetic oil must be considered.

For general hydraulic cylinders, cold and hot climate specifications may be available for use in different places of operation. In these cases, dedicated seal parts need to be used for individual purposes, which may result in higher cost, longer production lead time and other problems. In developing this new suspension cylinder, we carried out an immersion test on oil seals of proven materials or new dedicated materials under various conditions and then selected optimal oil seals for use at the assumed environmental temperatures and over the entire temperature range of the hydraulic fluid. This has allowed us to offer a universal cylinder specification, eliminating the need to set different specifications for various places in the world.

4.2 Hoist Cylinders

4.2.1 Downsizing

When the load-carrying body of a mining truck is lifted by extension of the hoist cylinders, the cylinder is applied with a substantial compressive load as a counterforce. In general, the diameter of this hydraulic hoist cylinder is decided more or less by the required thrust and the main relief pressure. For the telescopic type, however, the required thrust is not necessarily enough to decide the cylinder size because the buckling strength of the smallest rod of the cylinder may become an issue.

The telescopic cylinder has a structure in which a compressive load is directly applied to its smallest rod that is connected to the shaft of the vehicle body. When the cylinder starts extending from its retracted state, for instance, the smallest rod is applied with a substantial compressive load equivalent to a thrust, which can be calculated by multiplying the cross-sectional area of the 1st stage piston of the maximum external diameter with the internal pressure. If the smallest rod is sized up for higher buckling strength, the larger one outside the smallest rod will also have to be sized up, and then the next larger one will have to be sized up accordingly. As a result, the cylinder will be larger than the minimum size for the required thrust. How the buckling strength of the smallest rod can be attained for the required thrust is a key to a lighter and smaller cylinder. The hoist cylinder for mining trucks we developed uses high-strength, thick steel tubes to constitute the set of rods of a high buckling strength so as to be able to withstand the substantial compressive load. This design contributes to the downsized cylinder.

4.2.2 Strength to Withstand External Force and Pressure

The body of the mining truck substantially hangs over from the vehicle body towards the back, as shown in Photo 3. That is why the hinge pin that serves as a swing center for body lifting is located near the center of the body, not in the rear end of the body. When the body is lifted to let the load slip down the body surface, the body will be suddenly lifted like a seesaw with the load's own weight as soon as the load passes through the hinge pin. The load applied to the hoist cylinders then will be temporarily changed in direction from compression to tensile

(Photo 8). The magnitude of the tensile load occurring at the moment when the load slips down depends on the type and state of the load as well as the body profile.

If a large tensile load is applied to the cylinder during its extension, the rod chamber of the cylinder may reach the overload relief pressure set in the hydraulic circuit. A higher pressure in the rod chamber leads to a larger load applied to the seals of the individual rods and may jeopardize the structural durability of the rod chamber as a pressure vessel. With consideration given to the pressure and external force caused by the reversal of load, we selected an appropriate sealing system and designed the welding joint structure.

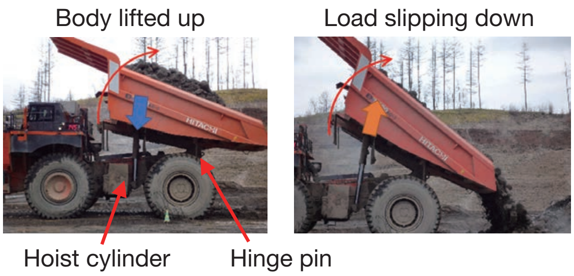

Photo 8 Reversal of load applied to hoist cylinder

4.2.3 Durability

Like the suspension cylinders, the hoist cylinders also need to be designed for long-term use with periodic overhaul activities. Structurally, the required durability should be determined by pressure frequency analyses of actual operation data. The durability is also supported by the welding joint structure of the high-pressure cylinders for hydraulic excavators.

As described above, the hoist cylinder is exposed to mud, sand and dust on site. It is thus necessary to design the cylinder on the assumption that these foreign materials will dry out and be adhered on the surface of the rod or will freeze at low temperatures. To prevent external oil leakage caused by damage in the rod surface or breakage of the rod seals due to the ingress of dust through the sliding parts of the piston rod, we developed a new excellent dust-proof seal jointly with a seal manufacturer. This dust seal is also used in the suspension cylinders.

5 Evaluation with Actual Vehicles

To validate the theoretical study and component test methods for the suspension and hoist cylinders for mining trucks, we mounted the cylinders we developed on an actual vehicle to conduct various evaluations in cooperation with Hitachi Construction Machinery.

5.1 Suspension cylinders

To finally validate the calculation models for the vehicle-holding and vibration-damping force characteristics set in section 4.1.1, we measured the holding force characteristics (Fig. 6) and the damping force characteristics

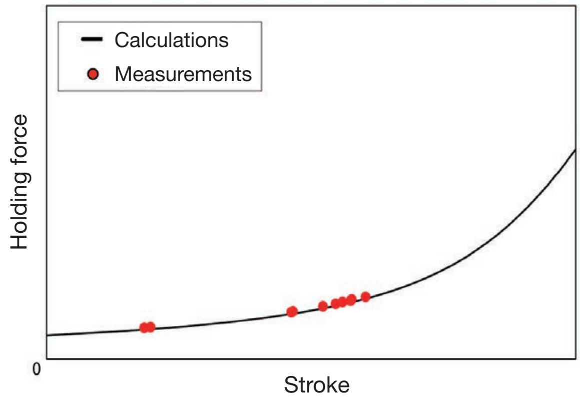

Fig. 6 Measurements of holding force characteristics of suspensions

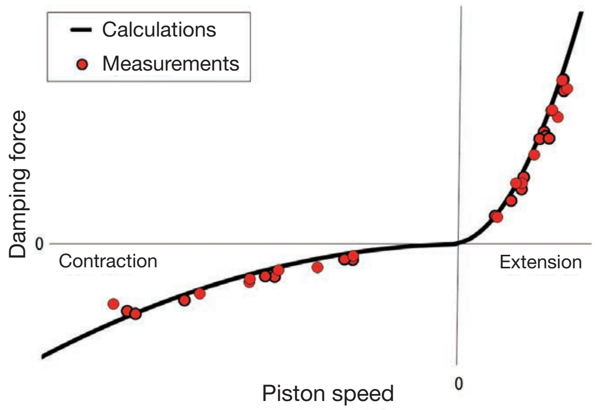

Fig. 7 Measurements of damping force characteristics of suspensions

(Fig. 7) of the suspension cylinders used in the actual vehicle.

Figs. 6 and 7 indicate that the calculations derived from the established models coincident well with the actual measurements. The validity of the calculation models for the holding and damping force characteristics has been verified. With these characteristics calculation models successfully created, we are now able to set these characteristics according to requests from customers through theoretical study alone, without fine-tuning by trial and error using actual vehicles.

In a test ride, those who took part in the sensory evaluation highly rated the suspensions, as indicated in feedback of, for example, "good riding comfort."

5.2 Hoist Cylinders

We measured the hydraulic pressure and external force applied to the hoist cylinders and determined the effect of the changes made on the cylinders on the vehicle body, including the stress of the vehicle frame. These loads were found to be not more than the assumed levels set in the theoretical study, with which we validated the design specifications. These loads were measured on the suspension cylinders as well.

6 In Closing

KYB's suspension and hoist cylinders have been used in Hitachi Construction Machinery's EH5000AC-3 mining truck (loaded vehicle mass: 500 tons) since they passed the evaluation test with the actual vehicle.

We successfully obtained knowledge specific to the products through the development and evaluation of the cylinder equipment for mining trucks. By making use of KYB's engineering expertise related to the design of high-pressure cylinders for hydraulic excavators and of hydraulic dampers for automobiles, KYB was able to design and manufacture cylinder equipment for mining trucks suited to the market applications and customer needs.

In this development project, we were fortunately able to evaluate the suspensions mounted on the actual vehicle in cooperation with Hitachi Construction Machinery. In fact, it is not easy to evaluate and verify the products on that huge actual vehicle. From now on, we will promote model-based development by deeply studying the basic technologies and simulation techniques.

6.1 Future Development of Cylinder Equipment for Mining Trucks

Internal engines and hydraulic equipment have been increasingly motorized. This trend is almost expanding into the field of construction machinery. Still, mining equipment, which is required to have high thrust and high capacity, is expected to continue using hydraulics. With this background, suspension and hoist cylinders for mining trucks are probably required to be further improved to deliver higher performance as follows:

6.1.1 Optimization of Suspension Cylinder Characteristics

With autonomous vehicles becoming popular, and as many mining trucks will be unmanned in the future, no importance will be placed on riding comfort. However, it will be difficult to drive the truck flexibly according to the road condition or to prevent load collapse that can be otherwise avoided by an experienced operator. Suspension cylinders will be required to offer optimal holding force and damping force characteristics, to reduce load applied to the vehicle structure, and ensure running stability under any traveling condition or any environment.

There are many possible solutions for hydraulic dampers for automobile applications to satisfy the requirements above, such as active suspensions to obtain optimal damping characteristics any time and cooperative control with the steering wheel. We will find an optimal strategy for suspensions for mining trucks and promote research and development towards its successful application.

6.1.2 Downsizing of Hoist Cylinders

Further downsizing of the hoist cylinders will enhance the design flexibility of the vehicle body. It is assumed that the structure of the vehicle body will change drastically when self-driving and other modern technologies become popular among mining trucks in the future, affecting how they are used on worksites. To contribute to the optimal vehicle design of mining trucks suited to the progress of the times, we will pursue a design technique for even smaller telescopic cylinders.

6.1.3 Integration of Hydraulic Equipment and Information Technology

The mining machinery industry has also increasingly introduced work efficiency improvement and self-driving with IoT, DX and other information technologies. It is an urgent challenge to integrate the hydraulic equipment with these information technologies.

Currently, KYB is developing a hydraulic fluid status monitoring system and a hydraulic cylinder failure detection system. Applying these systems to the cylinder equipment for mining trucks will make it possible to detect oil leakage and other failures earlier and to propose optimal overhaul timing to customers. We believe that these systems will allow mining trucks to offer even higher productivity.

Finally, we would like to take this opportunity to sincerely thank Hitachi Construction Machinery, all those concerned from related partners, and those concerned from related internal functions who gave us their cooperation for the development of this product.

References

1) Hitachi Construction Machinery; EH5000AC-3 Catalogue, EH5000AC-3 Feature and Specs Brochure
2) TAKAI: Changes in Cylinders for Hydraulic Excavators, KYB Technical Review No.50 (April 2015).
3) YOSHIDA, KAMEDA, HARA: Condition Monitoring System, KYB Technical Review No.60 (April 2020).
4) IWAMOTO, TAKAHASHI: Development of a Wireless Condition Monitoring System for Hydraulic Cylinders, KYB Technical Review No.61 (October 2020).

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Product Introduction

Development of "KADS" - An Electronically-Controlled Suspension System for Motorcycles

UEMURA Masashi, KOJIMA Hiroyuki, SUGAWARA Hidetoshi

1 Introduction

Motorcycles equipped with semi-active suspensions have been available in the European market since around 2012. These motorcycles are mainly sold in advanced models such as Adventure, Street, Tourer and Supersports. The market is still expanding and is expected to continue growing in the future too.

KYB has developed and commercialized a semi-active suspension system integrating the electronic control unit (hereinafter "ECU") hardware (hereinafter "HW") and software (hereinafter "SW"), tuning tools, sensors, front fork (hereinafter "FF") and rear cushion unit (hereinafter "RCU"). The following gives a general outline of the system.

2 Overview of System

2.1 System Components

Fig. 1 shows the components of the system. KYB is responsible for the development of the parts within the blue rectangle, and the customer is responsible for the development of the parts within the red rectangle.

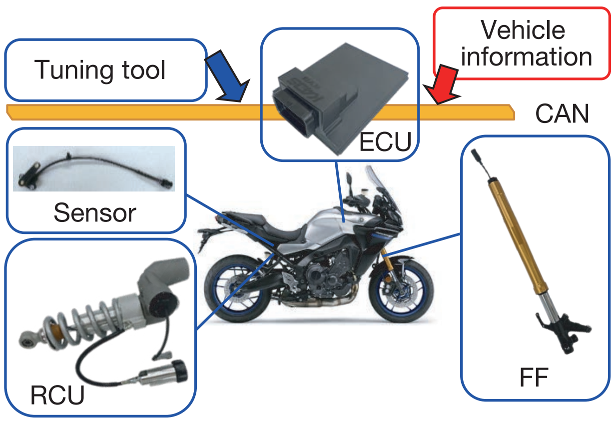


Fig. 1 Components of “KADS”

This new product has been achieved by integration of KYB-specific hydraulic and control technologies and is named "KADS" for branding (Fig. 2).

Fig. 2 “KADS” trademark

"KADS" Note 1) stands for KYB "Actimatic Damper System." The word Actimatic is a coined word from Active and Automatic and represents a high kinematic performance obtained through automatic adjustment. "KADS" achieves both the basic performance (riding comfort) and the kinematic performance focusing on the typical vehicle behaviors, i.e., "running," "cornering" and "braking."

Note 1) "KADS" and "Actimatic Damper System" are trademarks owned by KYB Corporation.

2.2 System Concept

"KADS" is based on KYB's original concept called "Ground-Hook," which provides the rider with the sensation of being grounded to the road - a feeling of security, just like a tire (Fig. 3).

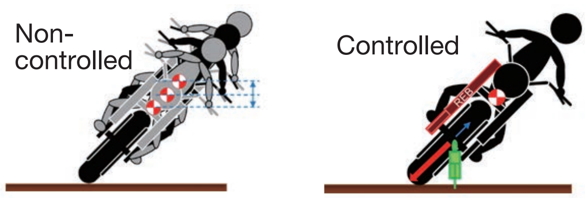


Fig. 3 Shift in center of gravity during cornering

Table 1 Center of gravity for controlled/non-controlled cases

Event	Control	Center of gravity	Effect (adhesion)
Shift in center of gravity	No	Unstable	No
	Yes	Stable	Yes

It may be difficult for beginner riders to maintain the banking angle properly against the vehicle speed while cornering. They are likely to apply the brakes or to put the motorcycle upright and often eventually make the center of gravity of the motorcycle unstable. For the non-controlled case, they can hardly stabilize the center of gravity, making the motorcycle unstable, as shown in Fig. 3. For the controlled case, "KADS" can automatically maintain the center of gravity to stabilize the motorcycle, and riders can easily feel the tire adhesion. This is called the riding skill support.

To realize the concept described in this section, we developed the products introduced in the following chapter.

3 ECU

The unique control system developed by KYB can detect the motorcycle condition in real time with information from multiple sensors mounted on the motorcycle and automatically adjust the damping force of the suspensions to an appropriate level according to the riding situation (running, cornering or braking). To provide optimal control based on the system concept, KYB newly developed HW and SW of the ECU.

3.1 Appearance and Structure

The appearance of the ECU is shown in Photo 1. A chip-mounted board is installed in the resin enclosure. The inside of the resin enclosure is filled with potting material to provide sealing and fixing to ensure resistance to vibration, water and dust (Photo 2).

Photo 1 Appearance of ECU

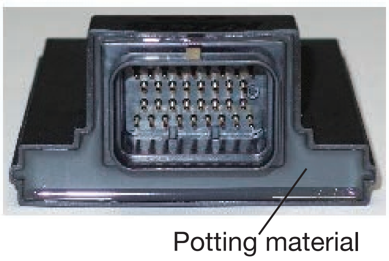


Photo 2 Filled with potting material

3.2 Interfaces

The ECU has connections to components, as shown in Fig. 4. The ECU provides interfaces with a Controller Area Network (hereinafter "CAN") and six analog input ports, enabling it to accept many different types of input. With these inputs, the ECU can control up to four solenoids. The ECU's highly flexible HW makes it possible to support a variety of interface requirements just by customizing the SW to the specifications of target motorcycle models.

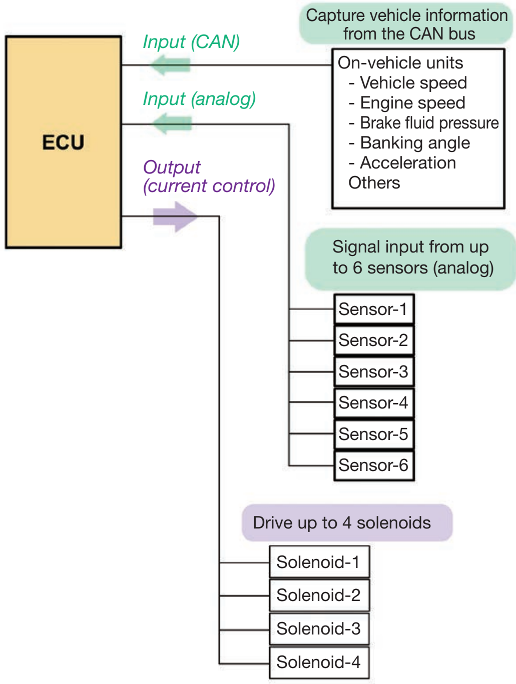


Fig. 4 Connections between ECU and components

Fig. 5 is a functional block diagram showing the general configuration of the ECU. This battery-powered ECU captures various input signals to perform calculation of damping force control. Its output section has a control switch and a current detection function, and puts out a desired current based on the results of calculation. The control switch is driven by pulse width modulation (PWM).

The ECU also has a safety mechanism that can detect and process anomalies. Should an anomaly occur, the mechanism works to initiate appropriate processing, causing the system to go to a safe state.

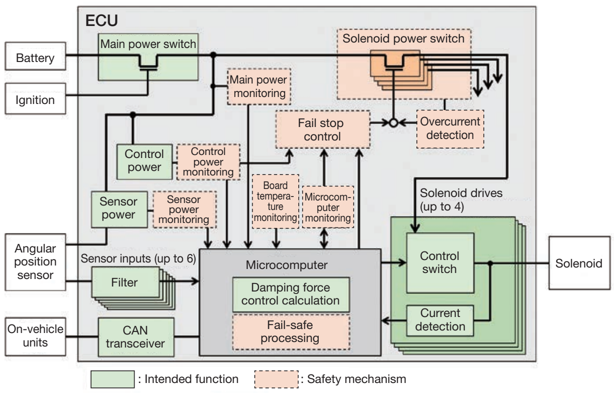


Fig. 5 ECU functional block diagram

3.2.1 Input to ECU

The ECU communicates with on-vehicle units via the

CAN bus to capture vehicle signals, including vehicle speed, engine speed, brake fluid pressure, banking angle and acceleration. It acquires sensor signals via the analog input port to detect the vehicle behavior. For "KADS," the angular position sensor described in Chapter 4 is mounted on the vehicle to detect the angle of oscillation of the rear swing arm. This sensor signal is captured via the analog input port.

3.2.2 Output from ECU

The output is connected to the solenoids integrated in the suspensions described in Chapter 5. Based on the calculation of damping force control, the current flowing through the solenoids is controlled. For "KADS," the damping force control covers three components: the left damper of FF, the right damper of FF, and RCU. The damping forces of these components can be independently controlled.

Table 2 Control logic list

Control name	Description
Pitching-based control	Adjusts the damping force according to the acceleration in the longitudinal direction of the vehicle. Suppresses nosedive.
Road surface condition-based control	Adjusts the damping force by determining the road surface condition based on the acceleration in the vertical direction of the vehicle.
Banking angle-based control	Adjusts the damping force according to the banking angle. Stabilizes the vehicle’s attitude during cornering.
Vehicle speed response control	Adjusts the damping force according to the vehicle speed.
Engine speed-based control	Adjusts the damping force according to the engine speed. Suppresses the abrupt changes in attitude of the motorcycle caused by the engine speed fluctuation.
Jump-based control	Adjusts the damping force by detecting vehicle jumps. Alleviates the impact on the motorcycle during landing.
Brake fluid pressure-based control	Adjusts the damping force according to the brake fluid pressure. Stabilizes the motorcycle during braking.
Stroke speed-based control	Adjusts the damping force according to the suspension stroke speed. Adjusts the basic characteristics to improve the ride quality.
Bottoming control	Adjusts the damping force to suppress bottoming of the suspensions.
Damping force correction control	Corrects the damping force by identifying the type of riding: solo, tandem, load.
Mode selection control	Enables the rider control such that the rider can freely select running modes.

3.3 Damping Force Control

To realize the "Ground-Hook" system concept, we built/integrated the 11 control logics listed in Table 2 to develop KYB's proprietary damping force control.

The ECU calculates the damping force control settings at a rate of 1/1,000 seconds in response to the signal inputs stated in section 3.2.1. With this high-speed processing, smooth control of the damping force has been realized. Parameters used for the control calculation can be flexibly set using a dedicated tuning tool according to the target motorcycle models.

3.4 Tuning Tool

KYB originally developed a tuning tool for setting parameters to control the damping force. Fig. 6 shows a conceptual illustration of the parameter settings. The use of the tuning tool allows the user to set in detail the damping force control characteristics for each input signal. To ensure usability, KYB provides vehicle manufacturers with this tuning tool as an application program that can be operated visually and intuitively. The tool makes it possible to adjust parameters efficiently in the actual vehicle evaluation, contributing to the shorter time of tuning of damping force in the development evaluation phase.

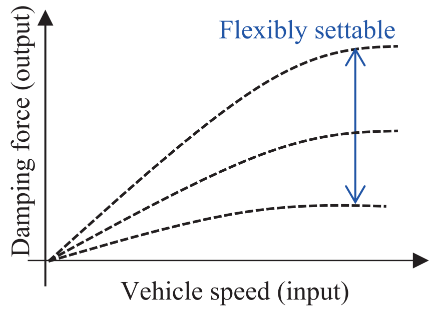


Fig. 6 Conceptual illustration of damping force control parameter settings

4 Angular Position Sensor

To achieve a sensor to detect the angle of oscillation of the rear swing arm, we adapted an existing product to develop a new angular position sensor.

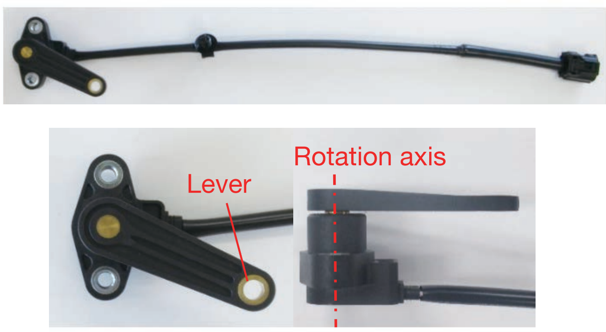


Photo 3 Appearance of angular position sensor

4.1 Appearance and Structure

The appearance of the angular position sensor is shown in Photo 3. The new sensor has a lever that is suitable for detecting the angle of oscillation of the rear swing arm. The sensor can be connected to the vehicle body via a rod installed at the tip of the lever so as to synchronize with the oscillating rear swing arm. The angle (angle of oscillation) is detected by the lever rotation.

4.2 Functions and Characteristics

This sensor includes a magnet and a Hall device to convert the mechanical rotation angle of the lever into an electric analog signal.

The effective range and output characteristics of this sensor are shown in Figs. 7 and 8, respectively. Over the effective range, the output characteristics are linear against the rotation angle of the lever, and the output voltage level is proportional to the power voltage supplied by the ECU. Thus, the sensor has a sufficient effective range and an adequate accuracy for detecting the angle of oscillation of the rear swing arm. This signal is also recognized by the ECU as one of the vehicle behaviors and is used as input for calculation of the damping force control.

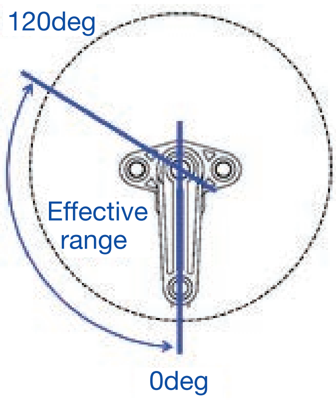


Fig. 7 Effective range

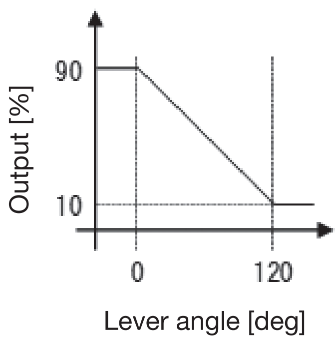


Fig. 8 Output characteristics

5 Suspensions

This new suspension uses a solenoid valve to offer a high reaction rate and generate a wider range of damping force than the conventional counterpart, thereby enabling a high degree of both handling stability and riding comfort simultaneously. To achieve an optimal damping force based on the system concept, we newly developed an FF, an RCU and a built-in solenoid.

For a higher reaction rate, the new suspension uses a proportional solenoid to convert electric energy into mechanical (linear) motion by means of an electromagnetic force.

5.1 FF

5.1.1 Basic Structure

Photo 4 shows the appearance of the new FF. This FF with a built-in solenoid has a solenoid valve installed within the damper and has an input current connector mounted outside the damper.

For the conventional suspension, several measures have been taken to improve the damping force or reaction rate, for example, the use of larger cylinders or pressurization of the hydraulic fluid.

For the new suspension, the use of larger cylinders is also applied. In addition, the right damper is equipped with a mechanism to produce an expansion damping force while the left damper has another to produce a contraction damping force. The use of these independent damping mechanisms eliminates the delay in response in generating a damping force during switch-over between expansion and contraction.

Photo 4 Appearance of new FF

5.1.2 Damping Force Characteristics

Fig. 9 shows the damping force characteristics for various methods of controlling the damping force. The method using a bypass oil passage with a needle valve can offer natural ride quality by making use of the valve characteristics, but only has a narrow range of damping force adjustability due to its structure.

For the relief pressure regulation method, it is possible to ensure an adequate range of damping force adjustability. However, it is unavoidable for the relief valve pressure regulation to start generating the damping force at a lower speed than the aforementioned needle valve method, making it difficult to ensure riding comfort of the motorcycle.

The new product further adopts a bypass oil passage method using a spool valve. This damping force generation mechanism consisting of a bypass oil passage based on the conventional type and a ganged valve can simultaneously provide both natural ride quality and a wide range of damping force adjustability equivalent to those of the conventional suspension.

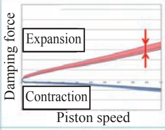
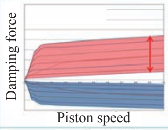
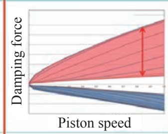
Method	Bypass oil passage with needle valve	Relief pressure regulation	New product Bypass oil passage with spool valve
Damping force characteristics			
Damping force adjustability	×	○	○
Ride quality of actual vehicle (evaluation results)	○	×	○

Fig. 9 Damping force characteristics

5.1.3 Solenoid Valve Structure

Fig. 10 shows, as an example, the structure of the solenoid valve in the expansion damping force generation mechanism (the right damper). The solenoid valve consists of a solenoid section, shown on the left-hand side of the figure, and a spool valve section, shown on the right-hand side.

The operating principle is that when the coil in the solenoid section is non-energized, the spool is pressed by the spring against the left-hand side, closing the soft passage to the holder. The total volume of the fluid flows into the hard passage of the hard valve, generating a high damping force.

When the coil is energized, a magnetic field exists around the coil, generating a force to attract the plunger to the base (an attraction force). This attraction force appears as a stroke of the plunger. The spool position is adjusted according to the input current to the solenoid, and the degree of opening of the soft passage is adjusted accordingly. This flow rate control can expand to switching over to the hard passage, offering a wider range of damping force adjustability. In other words, seamless switching from the soft passage to the hard passage and vice versa according to the input current value allows quick adjustment of damping force from low to high levels.

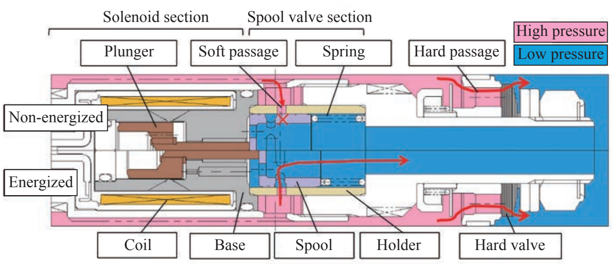


Fig. 10 Solenoid valve structure

5.1.4 Initial Spring Adjuster

Many FFs for sporty motorcycles have an initial spring adjusting mechanism. For semi-active FFs, the initial spring adjuster is generally located above the central axis of the dampers along with electric wiring, jeopardizing the ease of use. In this new product, an initial spring adjuster is located close to each of the dampers, not over the central axis, offering ease of use equivalent to that of the conventional suspension (Photo 5).

Photo 5 Appearance of initial spring adjuster

5.2 RCU

5.2.1 Basic Structure

Photo 6 shows the appearance of the RCU. Like the FF, the RCU has an internal solenoid: a solenoid valve is installed in the damper, and an input current connector is provided outside the damper. This double damper consists of an outer shell and a cylinder to guide the oil to the solenoid valve. In terms of damping force control, the bypass oil passage method using a spool valve is used as in the case of the FFs.

Photo 6 Appearance of RCU

5.2.2 Solenoid Valve Structure

The solenoid valve basically has the same structure as that of the FF. Fig. 11 shows the structure of the solenoid valve of the RCU.

For the RCU, only the expansion damping force can be adjusted. It uses a double-valve system that employs a soft passage with an internal soft valve. The damping force characteristics of the RCU focus on the low-piston-speed region to ensure high tire adhesion and suppress the attitude change of the vehicle during acceleration. The use of the soft valve helps compensate for the damping force in the low-speed region, achieving a smooth, luxurious and natural ride quality.

The operating principle is that when the solenoid is non-energized, the spool will not move to the right-hand side, closing the soft passage, as in the case of the FF. The total volume of the fluid flows into the hard valve provided on the damper side, generating a high damping force.

When the solenoid is energized, the spool moves to the right-hand side. The degree of opening of the soft passage is adjusted according to the input current to the solenoid. This regulates the flow into the soft valve, adjusting the damping force.

6 In Closing

KYB has completed the development and mass production of the new suspension product integrating different systems, which is the first time for the company to release for motorcycles. This makes it possible to deploy the suspension system to other categories of vehicles in a short time.

Mass production of this product has been launched in 2021 for use in TRACER9 GT ABS of Yamaha Motor Co., Ltd. It is under consideration to introduce the product into many other models of motorcycles. KYB is working on the application development.

Finally, we would like to take this opportunity to sincerely thank Yamaha Motor Co., Ltd., related partner manufacturers that gave us their cooperation for the development of this product, and all those concerned from related internal functions.

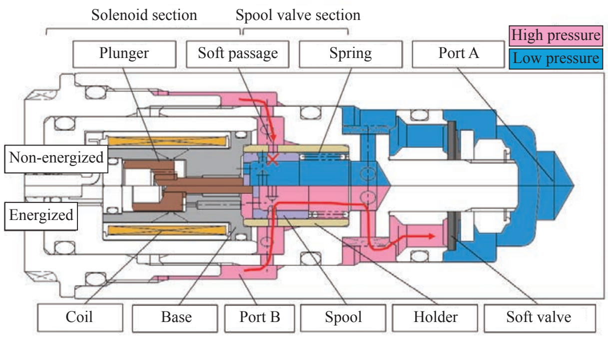


Fig. 11 Solenoid valve structure

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Technology Introduction

Research on SA-PS Integrated Control Technology

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1 Introduction

As driving automation technology enters widespread use in the future, about 30% of new automobiles are expected to be self-driving vehicles of Level 3 or higher in 2040 [1]. Accordingly, the needs for safety, security and riding comfort during automated driving will probably be higher and more diversified. To respond to these needs, KYB is making use of its strengths in shock absorbers (hereinafter "SA") and power steering (hereinafter "PS") to conduct research on an integrated SA-PS control technology to freely control the behavior of a vehicle. For improved safety and security of automated driving, it is indispensable for self-driving vehicles to run properly without wandering. A technology that allows these vehicles to correctly follow the target trajectory by suppressing the effect of uneven road surfaces is needed.

In this research, we applied the SA information associated with the vertical vibration of vehicles to the control of electronic power steering (hereinafter "EPS") as part of the development of an SA-PS integrated control technology. For this technology application, we addressed the development of two types of vehicle control: trajectory tracking control and anti-yaw control, as shown in Fig. 1.

Trajectory tracking control, which is now one of the basic technologies of the SA-PS integrated control technology, is an EPS control technique to allow the vehicle to accurately follow the target trajectory by making use of the information collected during automated driving. The anti-roll control uses the information from SAs subjected to vertical vibration to control the EPS, thereby suppressing the yawing associated with the vertical vibration.

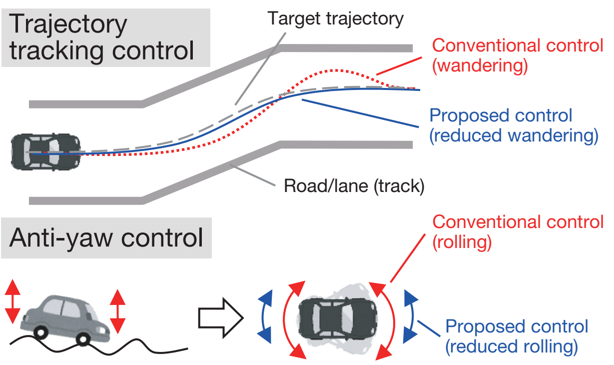

Fig. 1 Overview of SA-PS integrated control technology

2 Overview of Control System

This research used an experimental vehicle fabricated for the research and development of an SA-PS control system. This vehicle is designed to be able to automatically follow the path data within a test-driving course (a digital lane set on a map dataset) that was created in advance. This means that the experimental vehicle can only be run on the test-driving course. For the purpose of this paper, the experimental vehicle is classified as an automated steering vehicle since only steering control has been automated.

In the test, the brake and accelerator of the vehicle were applied manually, and the vehicle speed was maintained by the cruise control function provided as standard.

2.1 Control Components of Experimental Vehicle

Fig. 2 shows an overview of the equipment of the experimental vehicle. The experimental vehicle was fabricated based on a commercially available vehicle with additional sensors to measure the stroke (displacement) of the suspensions (hereinafter "stroke sensors"), acceleration sensors, and a GPS sensor capable of precisely locating

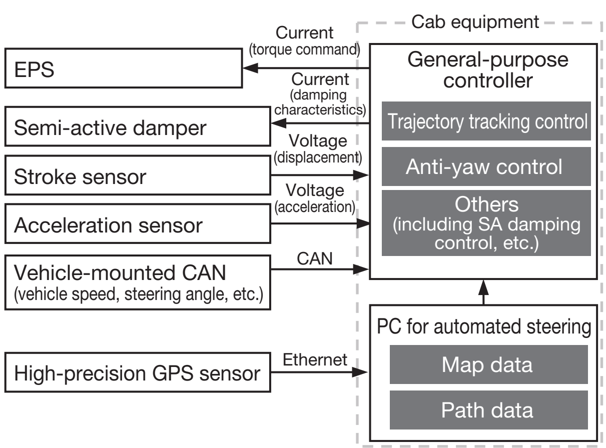

Fig. 2 Overview of equipment of experimental vehicle

the vehicle's position. Furthermore, a general-purpose controller and a personal computer (PC) system for automated steering were installed in the cab for the purpose of vehicle control.

As steering has been automated, the experimental vehicle uses an EPS prototype fabricated by KYB, which is connected to the general-purpose controller to achieve automatic control. The vehicle also has electronically controlled semi-active dampers made by KYB, which are also connected to the general-purpose controller to achieve automatic control.

2.2 System Configuration

Fig. 3 shows an overview of the control system configuration. Since the two types of control systems introduced in this paper mainly work for the EPS, Fig. 3 illustrates the connection to the EPS.

The PC for automated steering is installed with Autoware® Note 1) driving automation software. It also includes path data of the test-driving course that was designed and measured in advance. The PC for automated steering uses this path data and GPS positioning information to send information about the target paths nearby necessary for path following to the general-purpose controller.

The general-purpose controller has a control model created with MATLAB®/Simulink®. The controller performs even calculation of control commands (torque commands) given to the EPS necessary for path following.

Autoware® can originally calculate the steering angle necessary for path following from the path information and its own positional information. In this research, this function has been transferred to the general-purpose controller for improvement.

Note 1) Autoware®: An open-source software program for driving automation systems based on Linux and ROS, made public for the research and development of driving automation as part of the joint results of a project participated in by Nagoya University, Nagasaki University and National Institute of Advanced Industrial Science and Technology (AIST).

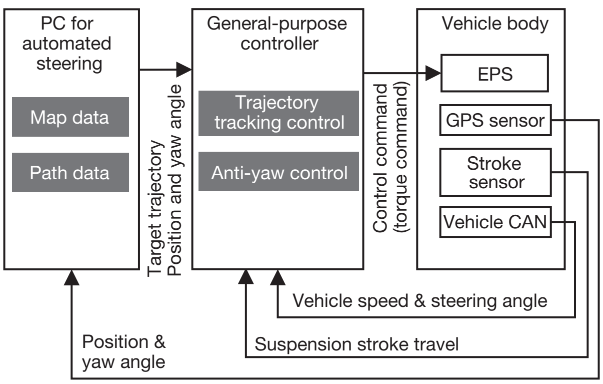

Fig. 3 Overview of system configuration

3 Design of Trajectory Tracking Control

One of the requirements for ensuring accurate tracking of a target trajectory is to suppress the delay in response to the yaw rate.

The delay in response to the yaw rate occurs in relation to various mechanical or physical characteristics of the vehicle during the transfer of the steering force to the vehicle body until the vehicle starts yawing. To eliminate the delay in response, the steering wheel should be operated to advance the phase according to the transfer characteristics, suppressing the delay in transfer of the force from the steering wheel to the vehicle.

One of the methods of eliminating the delay in response is model based predictive control. This method is often used in control systems in chemical plants or other facilities that involve relatively slow processes [2]. However, the method requires relatively complex procedures for calculation of constraints and optimization, posing the problem of time-consuming processing. Recently, the problem has been almost resolved by the use of processors or algorithms, but there still exists a high technical hurdle.

With the aim of implementing the control by as simple a method as possible, we developed in this research a trajectory tracking control system shown in Fig. 4. This control begins with prediction of the vehicle response: predicting the vehicle position and attitude during tracking of the target trajectory. It then goes on to yaw rate control that references to a future target value as far as the predicted response is delayed, thereby suppressing the delay.

After that is steering angle control. This control uses the inverse function of the EPS transfer function and introduces a 2-degree-of-freedom control that cancels the EPS transfer characteristics, suppressing the delay in response. Since an accurate differential value is needed to deal with the inverse function, the steering angle control accepts input of up to the second derivative of the target steering angle.

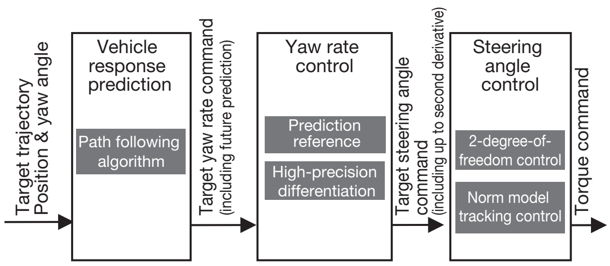

Fig. 4 Overview of trajectory tracking control

3.1 Path Following and Target Trajectory

For the purpose of this research, the path is defined as a route established on a map in advance, similar to a railroad track, and the target trajectory is defined as a route along which the vehicle should actually run while path following. The target trajectory greatly varies by the design concept or algorithm of driving automation. Particularly for running on a curved path or changing lanes, how the target trajectory is depicted against the established path affects the riding comfort and safety of the vehicle.

This research uses a tracking algorithm called the Pure Pursuit method [3], which is also used in Autoware®. A trajectory produced by the path following with this algorithm is defined as the target trajectory.

Fig. 5 shows an overview of the path following algorithm. The Pure Pursuit algorithm calculates the target yaw rate from a position that is some distance ahead of the vehicle on the path, called a lookahead distance, and its deviation from the path and then determines the steering angle based on the vehicle characteristics.

For performance evaluation, this path following algorithm was used to calculate in advance the vehicle's track against the path data of the test road. The resultant track was used as the target trajectory.

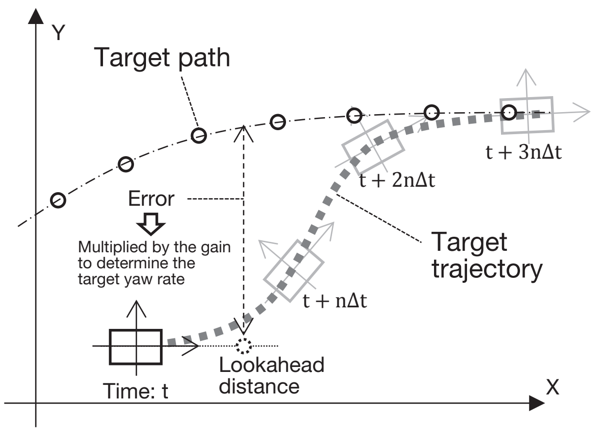

Fig. 5 Path following algorithm and target trajectory

3.2 Prediction of Vehicle Response

The location and attitude of the vehicle at any given future point in time can be predicted by calculating the response of the vehicle according to the tracking algorithm if the relationship between the current position of the vehicle and the path is known, although the accuracy is limited to some degree. With the aims of a reduced volume of calculation and simplified implementation of the system in this research, a 2-degree-of-freedom planar vehicle model was used to predict the vehicle response. Path following was performed according to the Pure Pursuit algorithm described in section 3.1. The changes in location and attitude of the vehicle per unit of time based on a discrete model were sequentially calculated to predict the yaw rate at future points in time up to one second ahead. Finally, the target yaw rate was determined.

3.3 Yaw Rate Control-Prediction Reference and Control

The vehicle's delay in response to the yaw rate can be predicted based on the vehicle characteristics as well as the vehicle's actual responses data. As in the reference to a target value based on the prediction as shown in Fig. 6, an estimated target value at a future point of time equivalent to the predicted delay in response is used to hopefully suppress the delay.

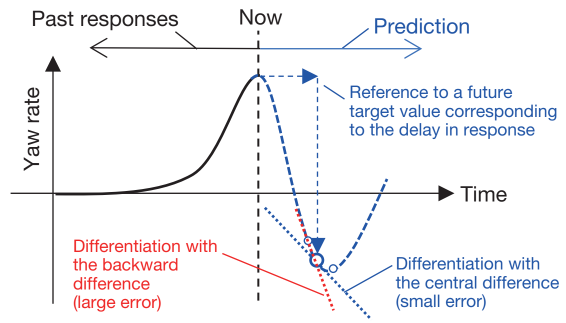

Fig. 6 Reference to predicted target value

Furthermore, the use of past and future values before and after the target value, respectively, makes it possible to obtain the approximation of up to the second derivative required to control the steering angle with a higher accuracy than with the central difference approximation.

The target yaw rate is controlled by a combination of the feedforward control that determines the steering angle with the vehicle speed gain with the vehicle stability factor [4] based on the vehicle characteristics taken into account and the feedback control that relies on the difference between the target yaw rate and the actual yaw rate.

3.4 2-degree-of-freedom Control Using Steering Angle Control-Prediction and Norm Model Tracking Control

As a method of suppressing the delay in response, 2-degree-of-freedom control is available. This method controls the target object by applying the inverse function, namely, the inverse characteristics, of the object's transfer characteristics to cancel the original transfer characteristics. However, the strict use of inverse functions requires highly accurate derivatives. Moreover, it is difficult to apply inverse functions to the EPS because of its complex characteristics.

In this research, we applied a combination of the 2-degree-of-freedom control and the norm model tracking control shown in Fig. 7 to control the steering angle.

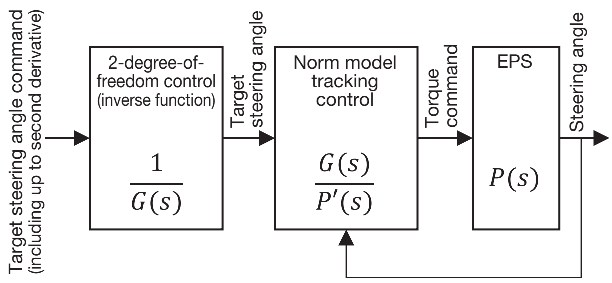

Fig. 7 Overview of EPS steering angle response delay control

When the EPS transfer function is $P(s)$, the norm model tracking control is first used to approximate the EPS response characteristics to a given transfer function $G(s)$ (norm model). In this process, the EPS transfer function is linearized to obtain the approximate transfer function $P'(s)$.

For the 2-degree-of-freedom control, the accurate derivative determined in section 3.3 is used to calculate the inverse function. Now the equation (1) below holds on the whole. The steering angle is controlled so that the input X ≒ the output Y.

$$\frac{\mathrm{Y}}{\mathrm{X}}=\frac{1}{G(s)}\frac{G(s)}{P'(s)}P(s)\fallingdotseq 1 \tag{1}$$

Since the use of the inverse function $1/P'(s)$ alone would deteriorate the performance if the EPS characteristics $P(s)$ change, we use the norm model control for approximation to the norm model $G(s)$ with the feedback control. This is intended to improve the robustness against disturbance.

The results of simulation of the steering angle control we developed are shown in Fig. 8. The word "Conventional" in the legend indicates the steering angle control installed on KYB's EPS prototype. "Proposed" shows the steering angle control attained in this research. For the trapezoidal waveform response (90 degrees at 4 sec.), which is one of the normal range response tests, the proposed control shows earlier response and earlier conversion with less overshoot than the conventional control. According to the step response diagram, the proposed control produces earlier response and earlier conversion than the conventional control as well, but with a little bit larger overshoot. This may be attributable to the model following error of the norm model control and/or the effect of the differentiation accuracy of the inverse function.

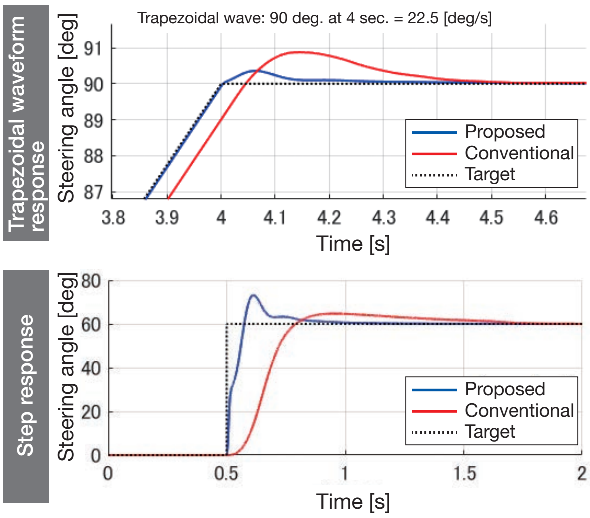

Fig. 8 EPS response to steering angle control

4 Design of Anti-yaw Control

When the vehicle vibrates up and down while running on an uneven road surface, the camber angle changes to generate a camber thrust[5)] due to the suspension geometry. In this case, the vehicle body may laterally swing to have a yaw rate.

In this research, such a yaw rate occurring during running on an uneven road surface is defined as rolling. We developed an anti-yaw control function to suppress the rolling by estimating the vehicle yawing based on the information collected from the stroke sensors mounted on the SAs and correcting the steering angle with the EPS.

4.1 Prediction of Vehicle Yawing from Strokes

The yaw rate of the vehicle attributable to running on an uneven road surface could be measured with a sensor such as an inertial measurement unit (IMU). Measurements obtained by such a sensor represent remaining vibration of the vehicle body after the occurrence. This implies that it is difficult to use these measurements to quickly suppress the yawing.

Another solution is to determine the stroke motion of the suspensions of the four-wheel car at the moment when the tires ride on an uneven road surface, thereby predicting the rolling. Based on the prediction, the steering can be controlled in advance to prevent the yawing just before the vibration is transferred from the vehicle axles to the body.

Fig. 9 shows the design of an anti-yaw control that we developed. This control design can achieve higher prediction accuracy by combining different prediction logics depending on the type of uneven road surface: for example, a road surface that causes both the front and rear wheels to yaw together or a road surface that causes the front and rear wheels to roll independently.

In particular, differentiating the difference in yaw between the front and rear wheels now enables prediction of the yawing caused by the torsion of the vehicle body when the wheels on one side of the vehicle ride on a step height.

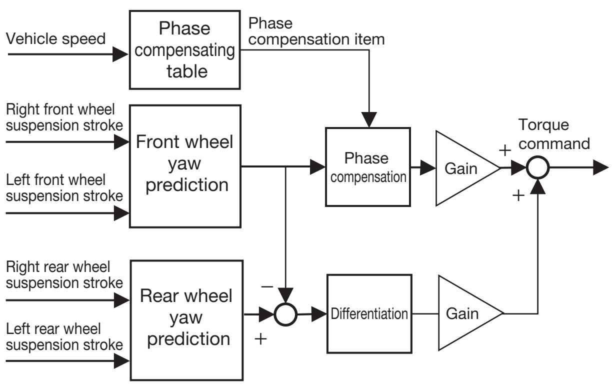

Fig. 9 Overview of anti-yaw control

4.2 Vehicle Response on Test Road Surface and its Prediction

We selected two different types of test road surfaces for verification and evaluation of the rolling of vehicles on uneven road surfaces. An overview of these test road surfaces is shown in Fig. 10. The cyclic wheels-on-both-sides vibrating road indicates a road surface on which the right and left tires of the vehicle running thereon alternately vibrate up and down. The single vibrating road has a step height of approximately 10 cm on which only the wheels on one side of the vehicle are riding.

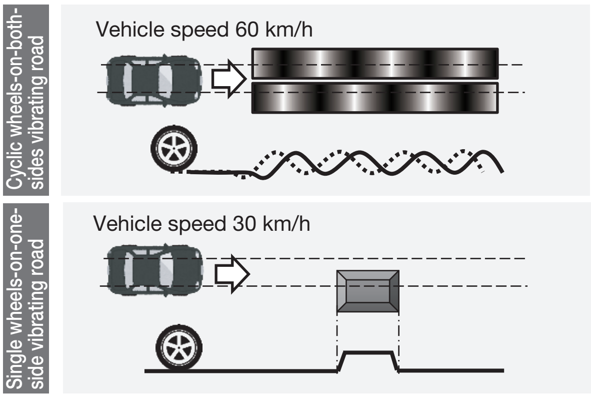

Fig. 10 Test road surface for yawing evaluation

In order to determine the occurrence of the yaw rate due to the uneven road surface and the accuracy of rolling prediction, the test vehicle with the anti-yawing control disabled was run on the uneven road surface straight ahead. The actual yaw rate response during the test along with the predicted yaw rate are shown in Fig. 11. The figure shows good results for the prediction of the yaw rate response based on the stroke motion with relatively high accuracy.

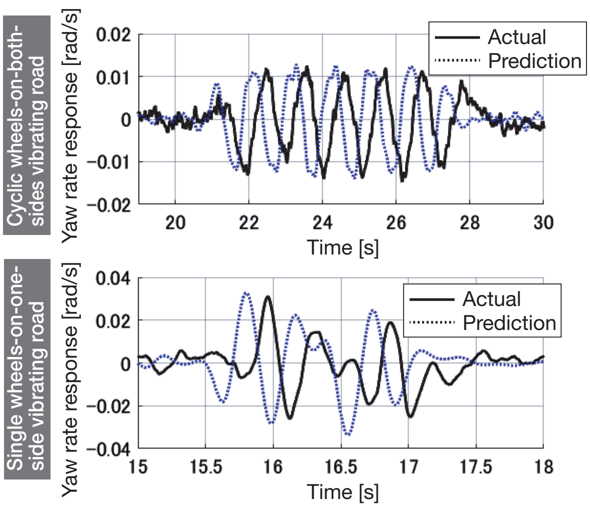

Fig. 11 Yaw rate response and prediction for vehicle running on test road surface

4.3 Prediction-based Yaw Suppression

Fig. 12 shows how the anti-yaw control command is input to the EPS. Predicted yawing is converted into a torque command by multiplying a gain, which is then added to the EPS torque command. Adding this converted value to the torque command whose response speed is very high can produce a sufficient allowance to cover the period of time from yawing prediction to suppression.

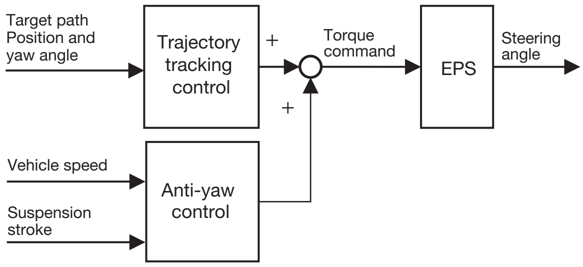

Fig. 12 Addition of anti-yaw control command

5 Evaluation of Trajectory Tracking Performance

In order to evaluate the tracking performance of the trajectory tracking control proposed in this research, a test was carried out on test courses. The test results were compared to those of the conventional feedforward control that determines the steering angle based on the target yaw rate command multiplied by the vehicle speed gain as described in section 3.3.

5.1 Performance Evaluation Conditions

As described in section 3.1, the Pure Pursuit path following algorithm was applied to obtain a track of the vehicle following the path data established on a map in an ideal way with no lateral slip. The track was used as the target trajectory.

The trajectory tracking error was defined as the distance between the center of gravity of the vehicle and the intersection of the target trajectory and the lateral line normal to the center of gravity of the vehicle, and then used for evaluation. For performance evaluation, the maximum trajectory tracking error was compared between the conventional and proposed controls to determine the error ratio to the conventional level.

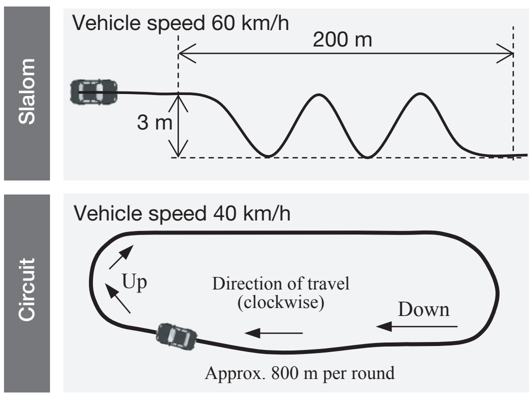

Fig. 13 Trajectory tracking performance test roads

In the test, the vehicle was run on a flat road surface slaloming at a vehicle speed of 60 km/h and on an up-and-down circuit road at a vehicle speed of 40 km/h as shown in Fig. 13, in order to measure the trajectory tracking error. The vehicle speed was maintained with automated steering during measurement.

5.2 Results of Performance Evaluation

Fig. 14 shows the results of the driving test. For each of the test roads, the tracking error from the target trajectory over the total travel is plotted. The proposed control only generates a trajectory tracking error of 35% of the conventional level at maximum for the slalom. For the circuit road, the error is substantially reduced in the curved sections. Though the vehicle was run at low speed, the proposed control is found to have the effect of error reduction even on the course with many disturbances, including up and down.

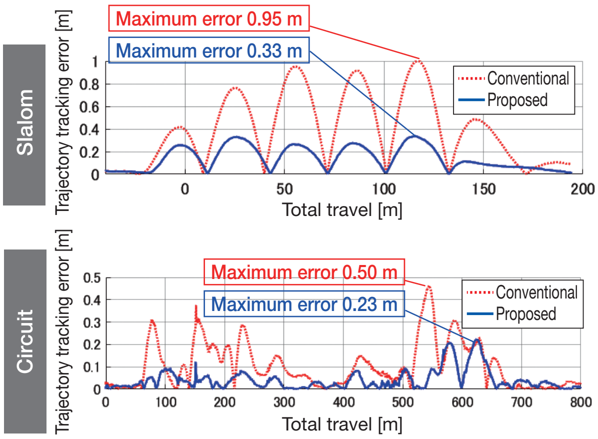

Fig. 14 Results of trajectory tracking performance evaluation

6 Evaluation of Anti-yaw Performance

In order to evaluate the proposed anti-yaw control for suppression of the yawing of the vehicle running on an uneven road surface, a test was carried out on test courses. The test results were compared to a case with no anti-yaw control.

6.1 Performance Evaluation Conditions

The anti-roll performance was evaluated with the PP value (the difference between maximum and minimum values) for the yaw rate measured with the on-vehicle IMU sensor. The ratio of the PP value of the proposed control to the PP value of the conventional one was calculated for comparison purposes.

The same test conditions related to the road surface and vehicle speed as those described in section 4.2 were applied. The test vehicle was run on the cyclic wheels-on-both-sides vibrating road at 60 km/h and run on the single wheels-on-one-side vibrating road straight ahead at 30 km/h. The actual yaw rate was measured.

6.2 Results of Performance Evaluation

The results of the performance evaluation test are shown in Fig. 15. The rolling has been reduced to 46% of the conventional level at maximum. In addition, the yaw rate is further reduced in positions near the intermediate point of the cyclic wheels-on-both-sides vibrating road.

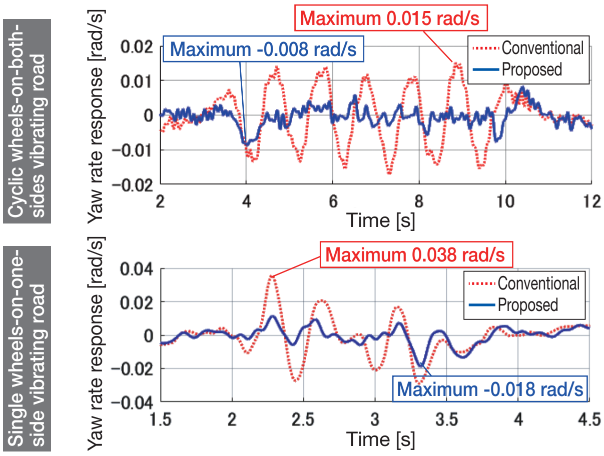

Fig. 15 Results of anti-roll performance evaluation

To determine the effect of the anti-yaw control, drivers from Experiment Dept., KYB, test-drove the vehicle to conduct sensory evaluation. As a result, positive comments were collected, including "the feel of rolling is better than before," "I felt zippy about the car rolling," and "the vertical shock feeling has been improved." Furthermore, it was also clarified that the reduced rolling affected the sensory evaluation about the vibration in the vertical and rolling directions.

On the other hand, comments like "with reduced yawing, I am annoyed by the vertical vibration" and "I cannot get well with any change in yawing (if the vertical vibration is terrible)" were collected. We eventually identified a challenge that it would be necessary to design and adjust the control and sensory effect with consideration given to a trade-off between yawing and vertical vibration.

7 In Closing

As an SA-PS integrated control technology for achieving improved safety, security and riding comfort during automated driving, we developed trajectory tracking control that allows vehicles to correctly follow the target trajectory, and anti-yaw control that can suppress the yawing of vehicles running on an uneven road surface. With these technologies, the tracking error for the target trajectory has been reduced to 35% of the conventional level at maximum and the yawing has been reduced to 46% of the conventional level at maximum. The anti-yaw control sensory evaluation has revealed that the control can deliver a certain effect of improvement but has given rise to a challenge that a trade-off between yawing and vertical vibration needs to be addressed.

By focusing on not only the yawing associated with the vertical vibration but also the vertical vibration involved in steering operation, we will promote the improvement of the SA-PS integrated control technology.

References

1) Fuji Chimera Research Institute, Inc.: Projection of the Favorite Next-generation Car Technology 2019 and the Vision of Future Automobiles (2019).

2) Jan M. Maciejowski/Translated into Japanese by ADACHI Shuichi, KANNO Masaaki: Predictive Control with Constraints, p.1-3 (2015).

3) R. Craig Conlter: Implementation of the Pure Pursuit Path Tracking Algorithm, Technical Report CMU-RI-TR-92-01 (1992).

4) ABE Masato: Motion and Control of Automobiles, p.72 (2009).

5) Editor: KYB Corporation: Structure, Theory and Evaluation of Automobile Suspensions, p.123 (2013).

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Glossary

Telescopic Cylinder

Refer to Development of Cylinder Equipment for Mining Dump Trucks (page 23)

NAKANO Tomokazu
KYB Technical Review Editor

1 What is a Telescopic Cylinder?

A telescopic cylinder, also called a multi-stage cylinder, is a cylinder with a multi-tube piston rod. This type of cylinder can provide a long output stroke from a compact retracted length and is generally used to raise and lower the load-carrying deck of a dump truck or in other similar applications.

2 Structure of Telescopic Cylinders

2.1 Structure

The telescopic cylinder has the same structure (structure type and support system) as the general single-acting cylinder except that the former has a multi-stage tube piston rod as described above.

An example of a structure of a telescopic cylinder is shown in Fig. 1. Structurally, this cylinder is a single-acting [Note 1] ram cylinder [Note 2]. The support system is of the clevis type on both ends. The number of stages is three.

Note 1) The single-acting telescopic cylinder is designed to operate under pressure only in one direction, i.e., extension or retraction. In the other direction, the cylinder operates using its own weight and/or the weight of the load. A telescopic cylinder designed to be extended and retracted under pressure in both directions is called a “double-acting type”.

Note 2) The ram cylinder has no hydraulic seal in its piston section. In this type of cylinder, the pressure sensing area matches the outside diameter of the rod. On the other hand, a cylinder with a seal in its piston section is called a “piston type”. In this type of cylinder, the pressure sensing area for extension is different from that for retraction (except for double-rod cylinders).

2.2 Cylinder Thrust and Stroke Speed

For the cylinder shown in Fig. 1, the pressure sensing area of each stage matches the outside diameter of the rod of the stage because it is the ram type.

For the piston type cylinder, the pressure sensing area for extension of each stage matches the diameter of the piston while the pressure sensing area for retraction matches the difference between the diameter of the piston and the outside diameter of the rod.

With these differences in pressure sensing area among stages, the ram cylinder provides the extension thrust and

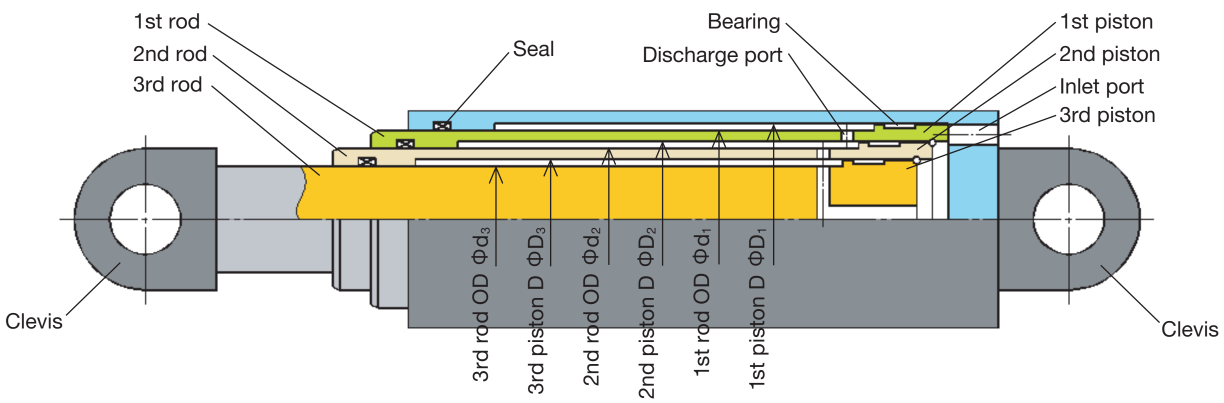


Fig. 1 Structure of telescopic cylinder (example)
(Single-acting, 3-stage ram cylinder with clevis support on both ends)

extension stroke speed progressively changing by stage as long as the pressure and flow rate to the cylinder are constant. The changes in thrust and speed can be expressed as follows:

- Cylinder thrust: 1st stage > 2nd stage > 3rd stage
- Stroke speed: 1st stage < 2nd stage < 3rd stage

3 Operating Principle

The operating sequence of the telescopic cylinder is shown in Fig. 2.

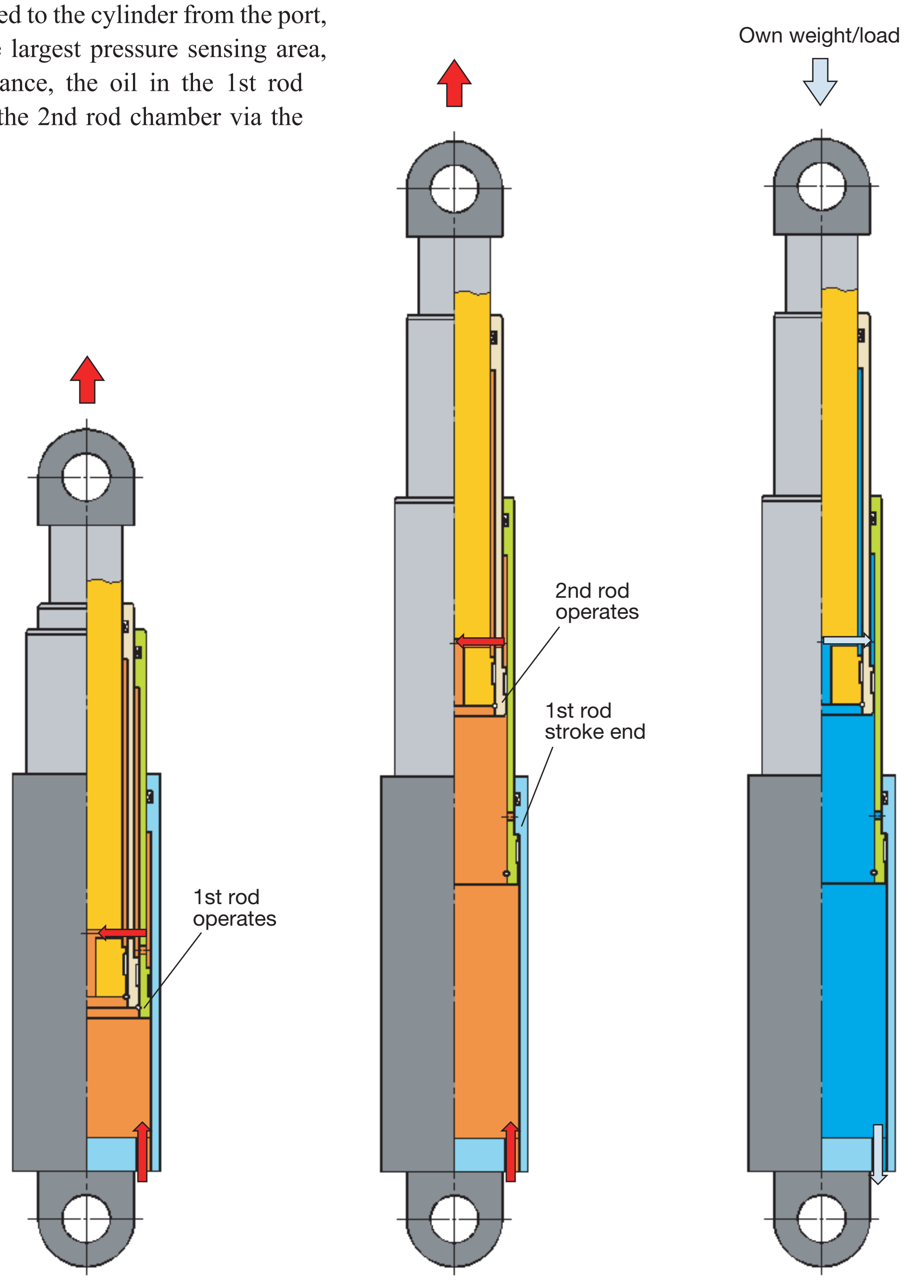
3.1 Extension Stroke

When a pressure is applied to the cylinder from the port, the 1st rod, which has the largest pressure sensing area, first operates. In this instance, the oil in the 1st rod chamber is discharged to the 2nd rod chamber via the discharge port.

When the 1st rod reaches the stroke end, the 2nd rod, which has the next larger pressure sensing area, operates. Thereafter, the remaining rods progressively operate in the same manner until the last rod reaches the stroke end. The total combined stroke length is the sum of the strokes of all the stages.

3.2 Retraction Stroke

The cylinder in this example retracts with its own weight and/or the load applied to the rods in reverse order to the case of extension stroke because it is the single-acting type.



(a) 1st stage extension (b) 2nd stage extension (c) Retraction

Fig. 2 Operating sequence of telescopic cylinder

Glossary

Pilot-operated

Refer to "Externally-Mounted Shock Absorber with Adjustable Solenoid Damping Force: Development of a New Type of Solenoid and Improvement of a Comfortable Ride and Quietness (page 3)"

KAWANO Yoshihiko
KYB Technical Review Editor

1 Pilot Control Valves

1.1 What is a Pilot Control Valve?

There are several types of hydraulic control valves in terms of operation method, including manual, mechanical, pilot and electromagnetic. Among these, the pilot-operated hydraulic control valve uses hydraulic pressure as a pilot signal (a pilot pressure) to forcefully open or close the valve body. Two types of pilot control valves are available: internal and external pilots. The internal pilot type uses the pressurized oil supplied to the valve for the pilot pressure signal while the external pilot type introduces the pressurized oil from another source of hydraulic pressure for the pilot pressure signal. These pilot-operated control valves include pilot relief valves and pilot check valves. The referenced article in this issue of KYB Technical Review particularly covers the pilot-operated relief valve. This glossary article explains the pilot-operated relief valve.

1.2 Relief Valves

A relief valve serves as a safety valve to allow oil to escape, preventing the hydraulic circuit from building up excessive pressure. The valve is also used to maintain the pressure in the circuit at a constant level. When the pressure reaches the setting for the valve, part or all of the oil in the circuit escapes to the reservoir. In terms of the operating principle, there are two types of valve mechanisms: direct-acting type and pilot-operated type. For the direct-acting type, when the hydraulic pressure applied to the valve body in the direction of opening increases to exceed the force applied to the valve body by the spring in the direction of closing, the main poppet is opened. For the pilot-operated type, when the hydraulic pressure increases to the setting or higher, a poppet valve in the pilot section is first opened, causing a pilot flow. When the pilot flow passes through an orifice, there arises a pressure difference across a balance piston, which opens the main valve.

1.3 Pilot-Operated Relief Valves

Fig. 1 shows an example of a pilot-operated relief valve. When the pressure in the high-pressure port increases to exceed the load applied by the pilot spring, the pilot poppet is opened to let the oil flow into the tank port. The flow creates a pressure difference across the orifice of the main poppet to let the high-pressure port oil flow into the tank port (Fig. 2). Compared to the direct-acting relief valve, the pilot type features a smaller body with better characteristics (a narrower override).

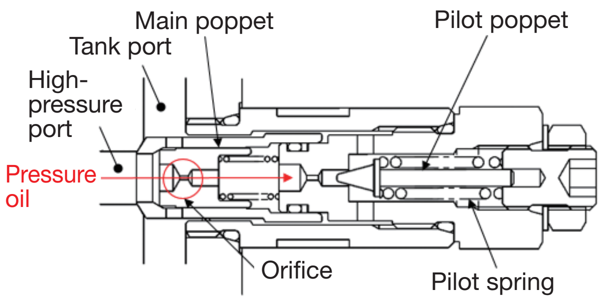


Fig. 1 Pilot-operated relief valve

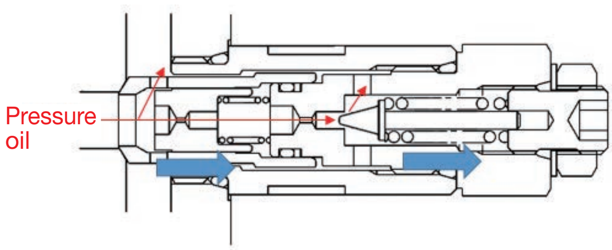


Fig. 2 Operation of pilot-operated relief valve

Glossary

Levels of Driving Automation

Refer to Research on SA-PS Integrated Control Technology

KABASAWA Ryoichi
KYB Technical Review Editor

1 Introduction

Automobile driving automation aims to enable the vehicle system to drive the vehicle itself autonomously and safely without human operation. Technologies considered indispensable to driving automation are called Advanced Safety Vehicle (ASV) technologies. An ASV is a vehicle equipped with a system that supports drivers to accomplish safe driving by making use of advanced technologies. To reduce the number of traffic accidents by commercialization of ASV technologies, Japan has promoted the development, commercialization and penetration of these technologies in the ASV Promotion Commission, whose members come from industry, academia and government.

2 Classification and Their Definitions

The categorization of driving automation in six levels, from Level 0 to Level 5, according to the Society of Automotive Engineers (SAE) standard SAE J3016 (2016) is generally used today.

In Japan, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has established a set of driving automation classes corresponding to the SAE categorization, including designation, vehicle type, and driving entity (Table 1), as well as definition (Table 2).

Autonomy in vehicles is categorized in levels according to the driving entity (driver or system), drivable area, the degree of maturity of ASV technologies and other factors.

Table 1 Classification of driving automation levels (prepared based on material from MLIT)

Level	Designation	Vehicle type	Driving entity
0	No driving automation	—	Human driver
1	Driver assistance	Driving-assisted car	
2	Partial driving automation		
3	Conditional driving automation	Conditional self-driving car (limited areas)	System
4	High driving automation	Self-driving car (limited areas)	
5	Full driving automation	Fully self-driving car	

Table 2 Definition of driving automation levels (created from material prepared by MLIT)

Level	Outline of definition
0	The driver takes full control of the vehicle.
1	Either acceleration/braking or steering is partially automated.
2	The automated system takes control of sub tasks for vehicle movement in the longitudinal and lateral directions in limited areas.
3	The automated system takes full control of dynamic driving tasks in limited areas. For any difficulties with operation continuation, the driver must intervene appropriately when called upon by the system to do so.
4	The automated system takes control of all dynamic driving tasks and responds to any difficulties with operation continuation in limited areas.
5	The automated system takes control of all dynamic driving tasks and responds to any difficulties with operation continuation with no limitations.

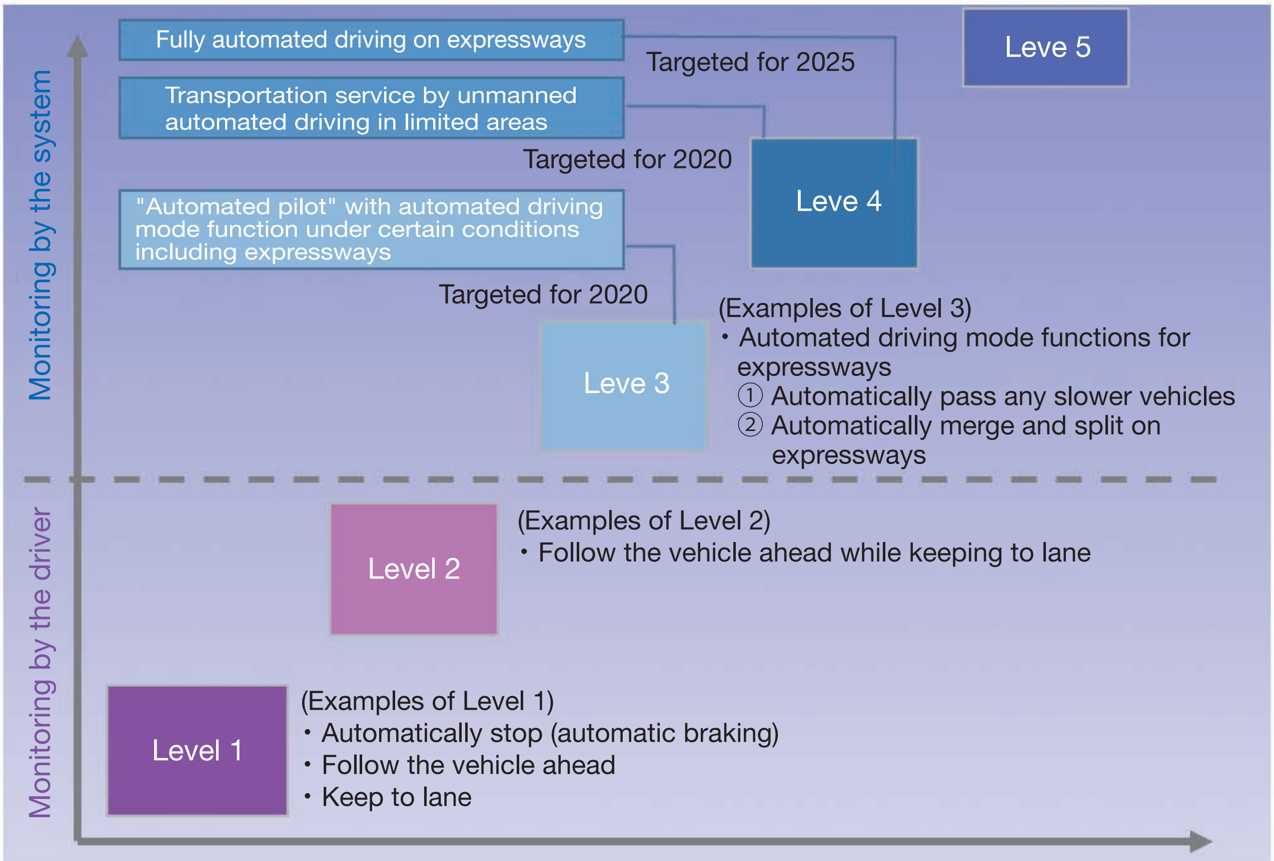


Fig. 1 Roadmap for driving automation (prepared based on material from MLIT)

3 Current Situation of Driving Automation

In Japan, legalization to allow Level 3 vehicles to run on public highways was made in April 2020. In November of the year, a conditional self-driving vehicle (Level 3) won type approval for the first time in the world. Previously in June of the year, the World Forum for the Harmonization of Vehicle Regulations (WP29) of the United Nations had adopted an international standard named the "Passenger Car Automated Driving Equipment Level 3", which is equivalent to the Japanese domestic counterpart. Thus, Japan has led the Level 3 technical standards. According to the Japanese Government, the implementation of Level 4 self-driving passenger cars for running on expressways is targeted for 2025 (Fig. 1).

The commercialization of or movement for commercialization of self-driving vehicles (Level 4) has been accelerated in other countries as well. In Germany, legalization has been enacted to allow Level 4 self-driving vehicles to run on public highways in certain limited areas in 2022. In the United States, a taxi dispatch service using unmanned self-driving cars was launched for the general public in October 2020. China started the commercial operation of Level 4 self-driving bus services in April 2021.

4 Prospects for Driving Automation

As driving automation technology has been commercialized, the automobile industry has increasingly promoted technical development to achieve the provision of new functional values. Along with the technical development, the United Nations WP29 promotes discussion towards the establishment of international safety standards and safety evaluation approaches.

References

1) Outline of Establishment of Schemes for Driving Automation. https://www.kantei.go.jp/jp/singi/it2/kettei/pdf/20180413/auto_drive.pdf
2) Efforts of the Ministry of Land, Infrastructure and Transport towards Implementation of Driving Automation. https://www.mlit.go.jp/common/001227121.pdf
3) Technical Guidelines for Safety of Self-driving Vehicles. https://www.mlit.go.jp/common/001253665.pdf
4) Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. https://www.jsae.or.jp/08std/data/DrivingAutomation/jaso_tp18004-18.pdf

Editors Script

This issue of KYB Technical Review (KYB TR) is No.63. KYB TR has introduced many different products developed by the company and released to the world so far. How have they fared after their release? Some should have been back on the KYB TR again after undergoing another evolution. But I wonder if some technologies have disappeared quietly or have not matched the needs of the age. If we look back on such marginalized products, we may perhaps see some other new thing from that horizon. KYB products have been manufactured for the purpose of contributing to society. Could it not happen that the product or technology at that time has evolved into another thing, helping people somewhere else? Could we not be able to find something new? How about such a plan to find an "after-sales" product? (OKAMURA)

Shameless! There is no other characteristic indispensable to clerical editors. In general, it is common for persons with backgrounds in liberal arts to build high inhibitions when they just hear the word "technology." The sentence given to me is to ask beginner's questions of those around me over and over again to feel ashamed as a representative of non-scientific readers. If the Technical Review were read by as many people as much as I feel ashamed, I can say I have the reason for my existence as an elected editor. The fact that I used to belong to Engineering is just between us. (MATSUMURA)

One and a half years have already passed since the COVID-19 pandemic began. You may spend each day feeling uncomfortable about everything under the 4th declaration of a state of emergency while the Tokyo Olympic games are going on. You may be stressed out, probably much more than you think yourself. In this situation, some of you may see and be moved by how the Olympic athletes play very hard without giving up to the end, being energized and encouraged. I'm very happy if those who read this KYB Technical Review will similarly address technical development or product development without giving up. (MARUYAMA)

KYB TECHNICAL REVIEW No.63

Published on October 1, 2021
Editor and Publisher: KYB Technical Review Editorial Board
Publishing Office: KYB Corporation
(On October 1, 2015, Kayaba Industry Co., Ltd. changed its trade name to KYB Corporation).
World Trade Center Building South Tower 28F, 2-4-1 Hamamatsu-cho, Minato-ku, Tokyo 105-5128, Japan
Tel: 03-3435-3511
Fax: 03-3436-6759
Printed by Shobi Printing Co., Ltd. (Hakusan, Tokyo)

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