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).

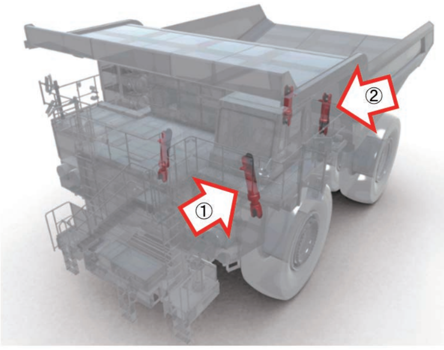

Fig. 1 Suspension cylinders

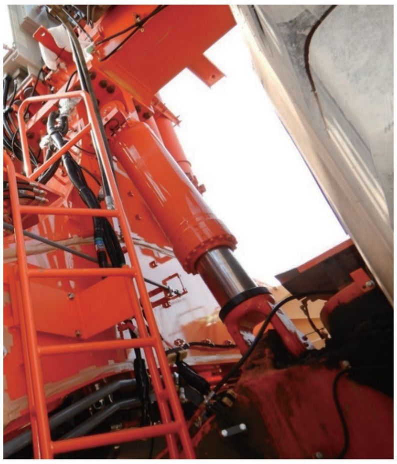

Photo 4 ① Front suspension cylinder

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

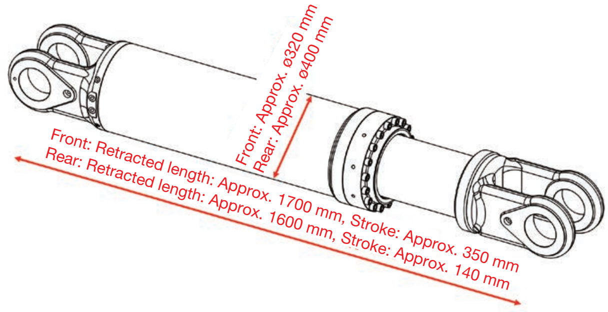

Fig. 2 Appearance of suspension cylinder

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.

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.

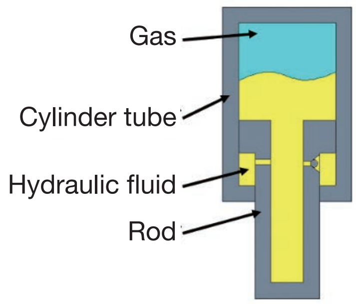

Fig. 3 Overview of suspension cylinder

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

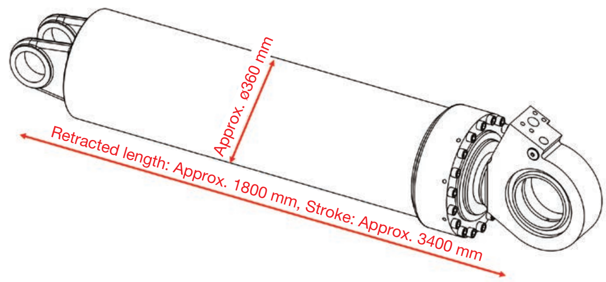

Fig. 4 Appearance of hoist cylinder

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

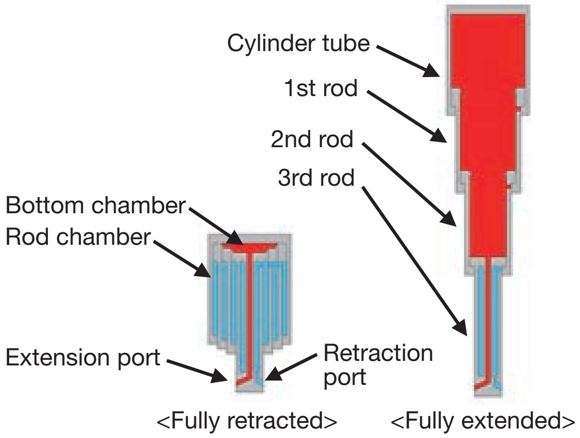

Fig. 5 Overview of hoist cylinder

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

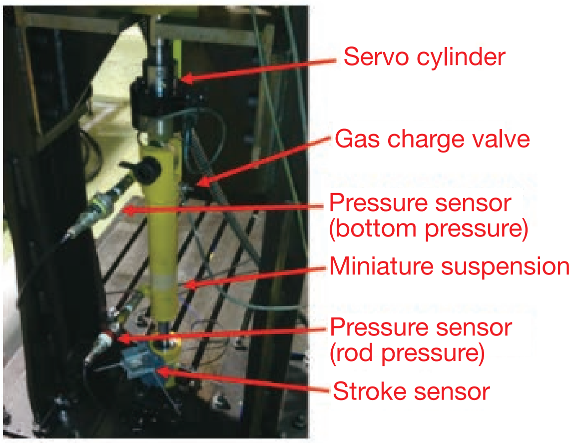

Photo 7 Miniature suspension

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.

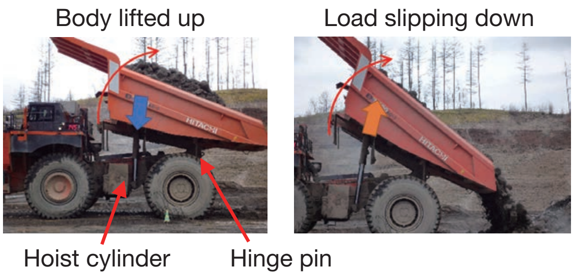

Photo 8 Reversal of load applied to hoist cylinder

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

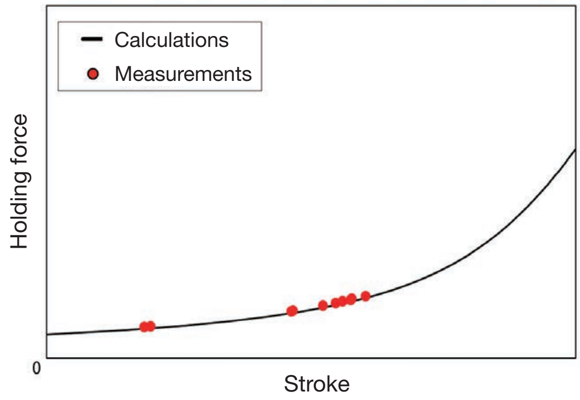

Fig. 6 Measurements of holding force characteristics of suspensions

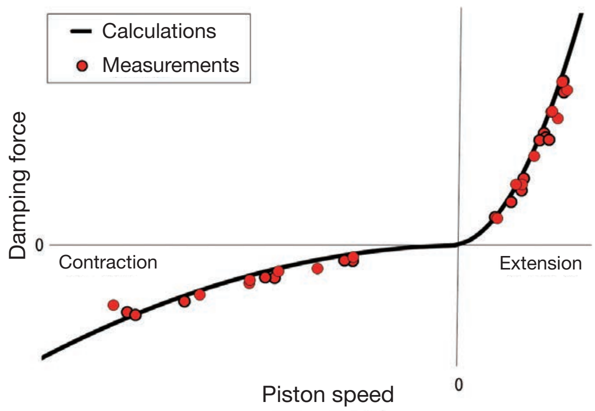

Fig. 7 Measurements of damping force characteristics of suspensions

(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.

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Author

TANIGAWA Natsuki

Joined the company in 2010.
Cylinder Design Sect., Engineering Dept., Gifu South Plant
Engineering Headquarters, Hydraulic Components Operations
Engaged in design and development of cylinder products for excavators.

HASEGAWA Kazuki

Joined the company in 2012.
Cylinder Design Sect., Engineering Dept., Gifu South Plant
Engineering Headquarters, Hydraulic Components Operations
Engaged in design and development of cylinder products for excavators.