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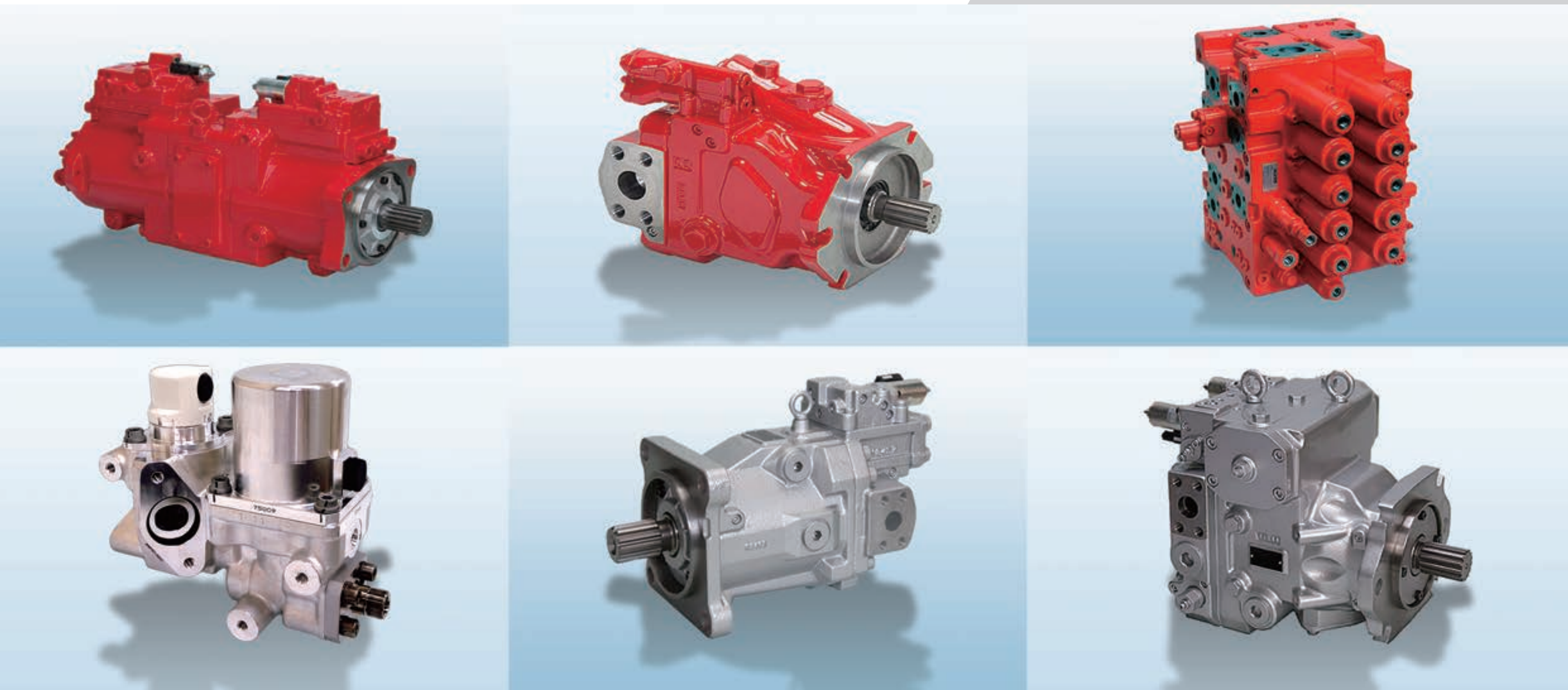
# KAWASAKI TECHNICAL REVIEW

## Special Issue on Precision Machinery



TECHNICAL REVIEW

No.181
May 2020

Kawasaki Heavy Industries, Ltd.


From the world's leading brand
to the global standard
ECO SERVO

# KAWASAKI TECHNICAL REVIEW

# No.181

Special Issue on Precision Machinery

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## Technical Description



## New Product Introduction

Interview with the Vice President and Senior Executive Officer

# The Present Situation of the Precision Machinery Business and its Development Going Forward

**Yasuhiko Hashimoto**
Representative Director, Vice President and Senior Executive Officer
Assistant to the President †

## How do you feel about the present situation of the precision machinery business?

The history of our precision machinery business dates back to 1916, when electro-hydraulic steering gear technology was first introduced from the UK. Since then, we have steadily developed our proprietary technologies, and now, we provide solutions around the globe in fields like construction machinery, industrial machinery, and marine machinery, with a focus on various types of hydraulic components.

The main products in our extensive lineup include hydraulic components such as pumps, motors, and valves; hydraulic equipment for industrial machinery; marine machinery such as deck machinery and steering gears; and electric control devices such as controllers. In 2018, we began the sales of high-pressure hydrogen regulators for fuel cell vehicles.

Today, products for construction machinery make up the majority of our sales. Excavators are one field of construction machinery where we are especially strong. Moving forward, we will continue to develop our strengths not only in excavators, but also in other fields of construction machinery and in agricultural machinery. From a global perspective, the growth rate

† At the time of writing
Director, Managing Executive Officer
President, Precision Machinery & Robot Company

of construction machinery and agricultural machinery exceeds the average growth rate of the world economy, and we expect that this robust growth will continue into the future.

## What is your future business strategy?

The Precision Machinery & Robot Company is comprised of the Precision Machinery Business Division and the Robot Business Division. As members of the same company, we will proactively work in a coordinated fashion to integrate robotics technology. For example, the movements of construction machinery share common features with the movements of robots. By applying the design and control technologies of robots to construction machinery devices and other products, we can explore new possibilities for products based on brand new ideas. Conversely, there will also be scenarios where we can apply the power mechanisms of hydraulic technology to robots.

Furthermore, technologies like ICT and IoT, which are starting to be used in fields like construction machinery, industrial machinery, and marine machinery, are proving to be very effective in failure detection, operator support, and for productivity and safety in general. These technologies are also shared by robots, which means further expansion of applications can be expected moving forward. We are also putting effort into the development of products that have advanced these technologies.

In addition, from the perspective of environmental protection, we expect environmental regulations such as those on exhaust gas to become even stricter around the world. Components of construction machinery such as diesel engines may eventually be replaced by electric motors. Even in these scenarios, hydraulics is a power transmission system with high flexibility, and with superb features such as shock resistance, they can be used in combination with electricity to develop new technologies and products.

## What is your technological strategy?

In order to improve the performance of products such as hydraulic components, we plan to fully utilize flow analysis, mechanical analysis, structural analysis, and various simulations while improving our capabilities for technological development.

In addition, in order to further strengthen our ICT and IoT technologies, we will also combine AI technology to pursue even more advanced technological developments. There will come a time in the future when construction machinery, agricultural machinery, and ships will become fully autonomous, fulfilling their functions without humans controlling them. In order to be able to provide solutions for this trend toward automation in terms of both ideas and equipment, we aim to continue making further progress and overcome challenges.

## Closing comments

We often hear about self-driving technology for automobiles in the media, but in construction and agriculture, where workforces are shrinking, automation and autonomous technologies are needed to be deployed more rapidly. In order to respond to these needs fast, we will continue to pursue innovative new technological developments that focus on the future.

# Market Environment and Product and Technology Developments in the Precision Machinery Field

**Hidehiko Shimamura**
Managing Executive Officer
President, Precision Machinery & Robot Company †

## Introduction

The products we are dealing with in the precision machinery field have been used in various industrial fields, contributing greatly to progress in relevant technologies. Combined with electronic control technology in an increasingly sophisticated manner, our business is expected to expand further with overwhelming power and high responsiveness, reliability, and flexibility.

In this article, I'd like to introduce the present market environment and our activities in the precision machinery field.

## 1 Features of the Precision Machinery Business Division

The Precision Machinery Business Division, formerly known as the Hydraulic Machinery Division, was established in 1968, marking its fiftieth anniversary in 2018. Currently, we are continuing to develop products in the fields of construction machinery, industrial machinery, and marine machinery that suit the needs of each of these fields with the aim of further expanding our business. We have been maintaining a high market share especially in the excavator field, which shows that the Kawasaki brand has penetrated into this field. Also, we are actively developing products in new fields, for example, hydrogen gas valves for fuel cell vehicles and motion control systems for construction machinery. We are constant working to further develop our business under the 2025 vision of becoming a "global-standard" motion control manufacturer that creates and offers total solutions with hydraulic devices and robots that overwhelm our competitors in terms of performance and quality, and total solutions as core products in automobile, construction machinery, electronics, and other industries and in the medical field.

## 2 Market environment and product developments in the precision machinery field

### (1) Excavator field

Because of an expanding global market, including China and India, the excavator market has become intensely competitive, and excavator manufacturers are working hard to differentiate their products. Developed in the pursuit of energy saving, hybrid systems are evolving rapidly, and excavator manufactures are developing models that can be used for computer-aided construction with ICT and IoT technology with the aim of achieving automation and full automation.

Also, they are working toward electrification to respond


(a) K7V Series (b) ERU2-7.0 (c) KMX Series

**Fig. 1 Hydraulic equipment in the excavator field**



† At the time of writing
Executive Officer
General Manager, Precision Machinery Business Division, Precision Machinery & Robot Company

to a future shift in power sources, and the excavator market is now in a state of major change.

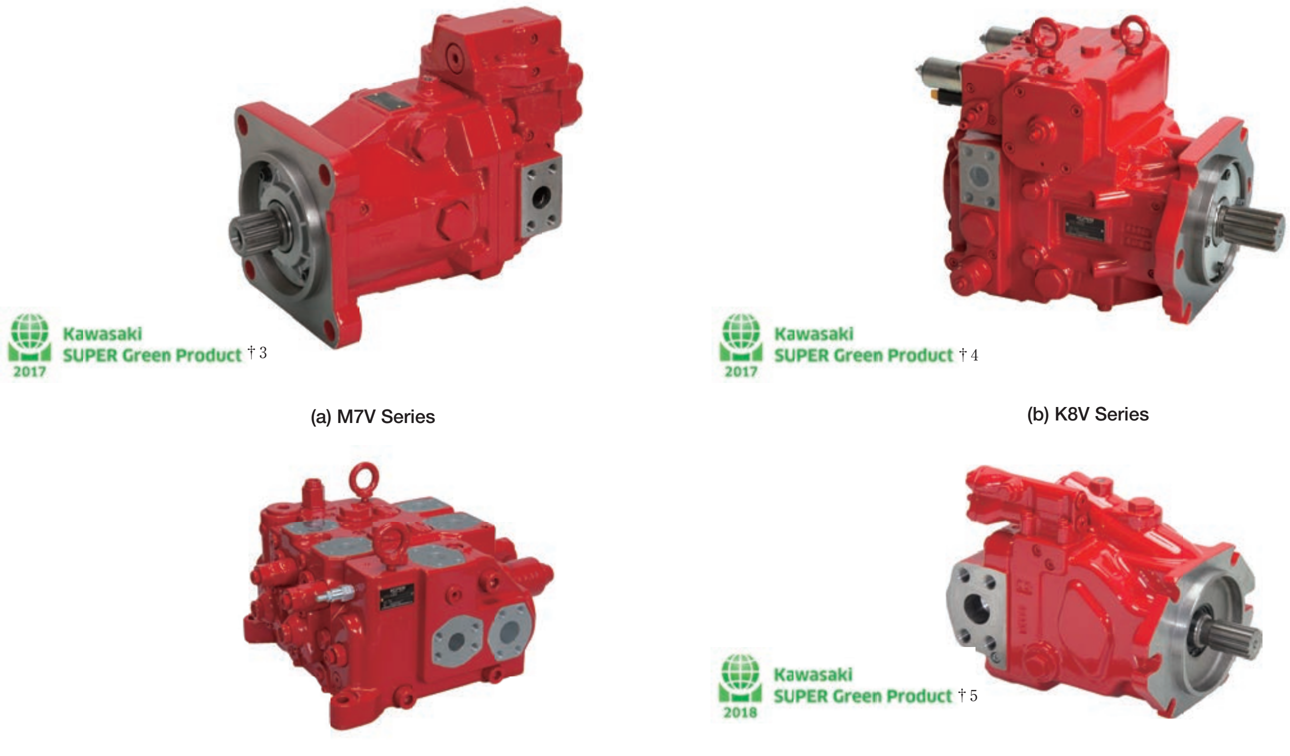
Offering high-performance products and responding closely to customers' requests, we have been increasing our market share in hydraulic pumps, motors, and valves (**Fig. 1**). Today, however, we are required to offer not merely hydraulic equipment but also hydraulic systems that can contribute to enhancing the value of excavators. Therefore, we are developing hydraulic systems with sophisticated controls and hydraulic equipment for these hydraulic systems.

Hydraulic equipment is required to have high performance that contributes to energy saving, high reliability for use in emerging countries and automation, and high controllability for use with sophisticated systems, and we have developed technologies necessary for individual products and put those products on the market. For hydraulic pumps, which greatly affect the energy efficiency and reliability of excavators, we have developed the K7V Series, which features high efficiency and high power density, to enhance the lineup of this series. We used the research results we have accumulated over the course of many years to design the rotary of the K7V Series, thereby achieving the world's highest level of efficiency. As for KMX Series control valves, we have developed a new series that significantly reduces pressure loss with fluid analysis and supports electronic control that enables advanced control with the aim of pursuing energy saving and higher operability. In addition, we have put low-hysteresis, compact electromagnetic proportional solenoid valves and electric joysticks with high operability on the market, both of which are essential in electronic control systems. We will be working to develop technologies necessary to reduce pump noise and increase pump speed for future electrification of drive systems.

**(2) Mobile machinery field**

The "mobile machinery field" is a generic term for fields other than the excavator field. Various machines including construction machinery are used in a variety of fields. These machines are manufactured by many different manufacturers, including large manufactures and small niche manufacturers, forming a larger market than the excavator market. In the mobile machinery field, manufacturers are required to show their presence to be recognized as a global-standard company, and we are also working with our group companies to make a full-scale entry into this field.

The equipment specifications and load conditions required in the mobile machinery field are different from those required in the excavator field, so the products made for excavators may not be suitable in this market. Therefore, we have been developing products suited to the specifications and characteristics required in the mobile machinery field by using the technologies we have developed for excavators (**Fig. 2**).



(a) M7V Series

(b) K8V Series

(c) KLSV Series

(d) K3VLS Series

**Fig. 2 Hydraulic equipment for the mobile field**

† 1 The K7V Series, a high-efficiency, low-noise, compact, and high-reliability hydraulic pump, has been widely used for construction machinery (mainly excavators).

We developed six different sizes of the K3VLS Series middle pressure pumps, which have already been adopted for machines in various fields. Also, we developed M7V Series swash plate motors as high-speed motors used mainly for crane winding. Moreover, we developed K8V Series pumps for closed circuits, as well as a controller for this series, making a full-scale entry into the HST (Hydro-Static Transmission) system market with the combination of the M7V Series and K8V Series.

We are developing valves for various machines as well. We are offering various control valves for load sensing systems, which are most commonly used in the mobile machinery field, with the KLSV series, including valves for concrete pump trucks. We often receive orders for these products made for the mobile machinery field from big manufacturers we have earned trust with in the excavator field, so further sales expansion can be expected.

Currently, we are offering technologies and products for the mobile machinery field and developing pumps and control valves for tractors with the aim of making a full-scale entry into the agricultural machinery field.

### (3) Industrial machinery field

We are offering various kinds of hydraulic equipment and systems characterized mainly by high-responsiveness, high-accuracy control technologies, especially equipment for high-pressure, large machinery, for a wide range of fields, including steal making plants, press machinery, and other kinds of industrial machinery.

Environmental and resource issues are still gathering attention, so technologies must take the future global environment into account. Kawasaki has put hydraulic equipment and systems that can contribute to energy saving on the market. For industrial machinery, we put ECO SERVO (**Fig. 3**) on the market, which is an electro-hydraulic hybrid system characterized mainly by its high energy saving effect, small size, high maintainability, low noise, and high controllability. Also, we have added products combined with a high-pressure, high-capacity pump with a discharge pressure of 35 MPa and displacement of 500 $cm^3$ to our lineup for the forging press market where high pressure, high flow rate, and high accuracy are required.

### (4) Marine machinery

We offer two kinds of marine machinery: steering gears (**Fig. 4**), which are installed in the stern and used to move the rudder according to the order signal from the steering stand on the steering bridge, and deck machinery typified by windlasses, which are used to raise and lower the anchor when anchoring a ship at sea, and mooring winches, which are used to wind and unwind the rope when berthing and mooring a ship.

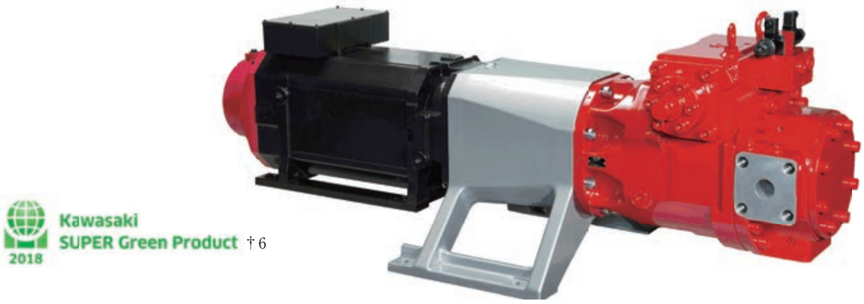



Fig. 3 ECO SERVO

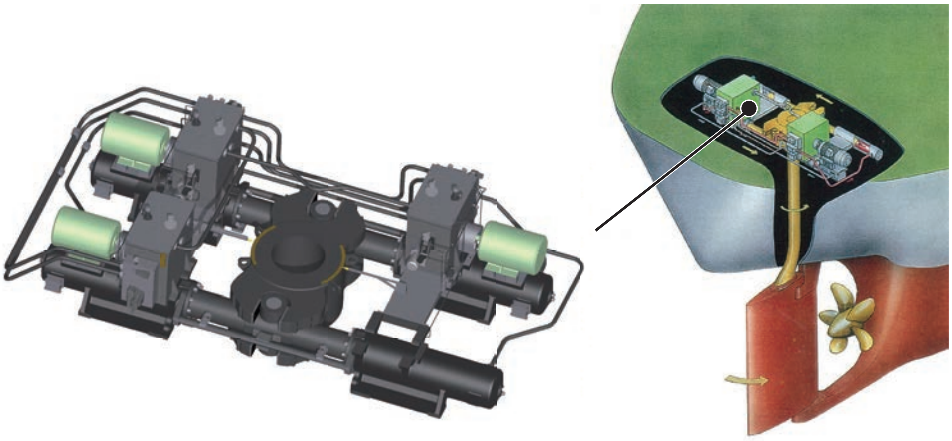


Fig. 4 Steering gear



† 2 ERU2-7.0, an electric joystick used for operating construction machinery, has significantly reduced power consumption and best-in-class durability at the same time.

† 3 The M7V Series, a hydraulic motor with the world's highest power density and low noise, is suited mainly to HST drive and winch winding systems in industrial vehicles.

Steering gears and deck machinery use oil pressure to generate and transmit power, and our products have been installed in many ships, contributing to safe navigation. Considering its reliability and output characteristics, we expect the electro-hydraulic system to continue to be the mainstream.

Steering gears are one of the most important pieces of equipment in ship handling, so the systems are made redundant, and the crew check the condition of these gears for failure prevention in the conventional way. However, as the automation of ships progresses and they come to be operated with smaller crews, failure prediction technology will become more important, by which problems are predicted by means of sensors and data analysis to prevent failures. It is possible to collect detailed data on the condition of the steering gear by installing sensors onto the steering gear to monitor pressure, flow rate, oil temperature, motor power consumption, and so on and installing a high-speed data logger with large-capacity storage in the ship. The collected steering gear data is analyzed to detect abnormal parameters and predict failures, thereby notifying the ship owner of the appropriate timing for maintenance and enhancing the reliability of the steering gear.

We have installed a steering gear with sensing technology and a high-speed data logger in a very large crude oil carrier (VLCC) and are collecting data. Based on this data, we are developing our failure prediction technology, which is scheduled to be completed in fiscal 2020.

**(5) New business fields**

Amid a growing interest in global environmental issues, including efforts toward zero $CO_2$ emissions, fuel cell vehicles (FCVs), which allow hydrogen stored in the vehicle to react chemically with oxygen in the atmosphere in the fuel cell and drive the motor to run, are drawing attention. FCVs are characterized by their shorter fueling times and longer cruising ranges than electric vehicles (EVs) and are expected to spread if sufficient infrastructure is provided. It is said that by the 2040's, electrically powered vehicles will have spread all around the world and that FCVs and EVs will both be in use all over the world.

Based on high-pressure gas control technologies we have accumulated for defense products, we began developing hydrogen gas valves for fuel cell vehicles in 2001. We developed and delivered prototypes with automobile manufactures and industrial vehicle manufactures, and began full-scale development for mass production around 2014. Today, we are mass-producing and delivering tank valves, which are used to open and close the tank, and high-pressure regulators that reduce the tank pressure from 70 MPa to approx.1 MPa, as core products, to automobile and industrial vehicle manufactures. Daimler AG has adopted our hydrogen regulator (**Fig. 5**) for the Mercedes-Benz GLC F-CELL, and we began shipping it in January 2018.

We are dedicated to using hydrogen energy, which is friendly to the environment. These products play a part in the realization of the "Hydrogen Road" in terms of hydrogen use. Through these developments, we desire to show a new future brought about by hydrogen energy to people all around the world.

## 3 Technological developments for the future

**(1) Machine control technology**

We have been designing and manufacturing the various kinds of hydraulic equipment that moves construction machinery, including the hydraulic pumps that work as if the heart of construction machinery. In recent years, we

Kawasaki SUPER Green Product †7
2019

**Fig. 5 The KGPR65D high-pressure hydrogen regulator for fuel cells**

† 4 The K8V Series, a dual-tilting hydraulic pump with the world's highest-level pump efficiency and low noise, is suited to closed-circuit systems, such as HST drive systems, in industrial vehicles.

have started developing controllers that integrally control hydraulic equipment, covering everything related to the motion control of construction machinery.

In the construction industry, improvements in efficiency, safety, and working environment are required, as they are lagging behind other industries. In addition, the workforce shortage due to the aging population is a big issue. Given this situation, automating construction machinery and improving the efficiency of construction work using electronic control technology, ICT, and IoT technology is becoming a major trend.

Aiming to achieve a global standard in the motion control of construction machinery, we have started developing machine control technologies in addition to hydraulic systems for automated construction machinery to address the automation of construction machinery. For example, excavators can perform various types of work but their operation relies on skilled operators. Automating such machinery requires a good understanding of the characteristics of hydraulic equipment as well as excellent control technologies. We are professionals in the fields of hydraulic equipment and hydraulic control technology and have excellent know-how on controls in the robot business field, such as tracking control and damping control.

We first developed the 2D machine control system by combining hydraulic technologies and ICT, IoT, and robot technologies (**Fig. 6**). The 2D machine control assists operators to enable even unskilled operators to work almost in the same way as skilled operators. We are continuously developing the 3D machine control systems with higher levels of sophistication by using the global navigation satellite system among other means.

**(2) Electro-hydraulic actuator-related technologies**

We are developing humanoid robots, which can work in place of humans in areas that are dangerous to humans, such as disaster sites, or in severe environments, such as high temperature and radiation environments. These robots use electric actuators, but we are thinking of adopting electro-hydraulic actuators, which use oil pressure, to further enhance robustness, including shock resistance. Currently, we have put a variable speed control electro-hydraulic actuator for industrial equipment on the market, which uses a servo motor to drive a hydraulic pump. Using this electro-hydraulic actuator technology, we are developing Hydro Servo Muscle (**Fig. 7**), which is an ultra-compact and -lightweight electro-hydraulic actuator with a variable capacity pump that can be mounted in humanoid

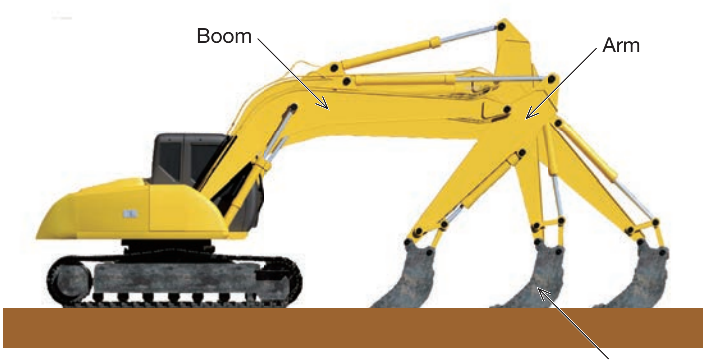



**Fig. 6 2D machine control**

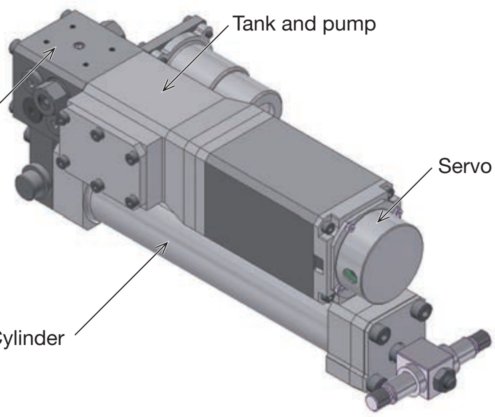



**Fig. 7 Hydro Servo Muscle**



† 5 The K3VLS Series, a hydraulic pump for mobile machinery with the industry's highest-level pump efficiency and low noise, contributes to improving the fuel consumption of construction machinery.

† 6 ECO SERVO, an electro-hydraulic hybrid system controlling the pump speed according to the hydraulic pump power that runs the hydraulic drive system, achieves energy saving and noise reduction.

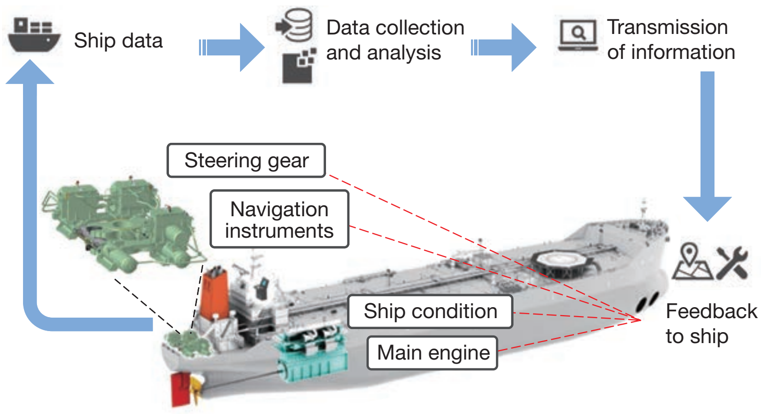



Fig. 8  Advisory service

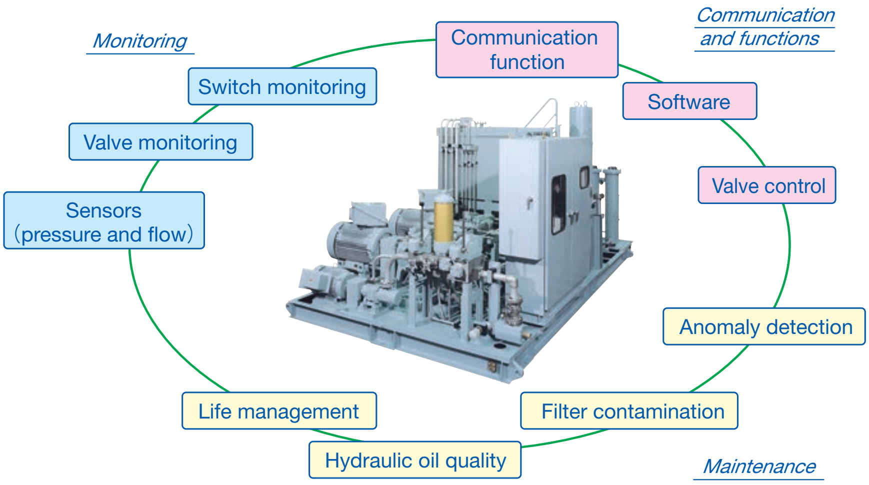



Fig. 9  Condition monitoring of hydraulic unit

robots. In addition, we are developing compact electro-hydraulic actuators for industrial applications.

**(3) Utilization of ICT and IoT technology**

ICT and IoT technology are used more and more in the marine machinery industry, including, for example, advisory services for monitoring ship conditions and optimizing maintenance. Sensors are used to collect various kinds of data in a ship, and that data is then sent to an on-shore facility. After the data is analyzed, feedback, including ship condition and maintenance timing, are sent to the ship (**Fig. 8**). Also, for steering gears, failure diagnosis sensing will be performed for condition monitoring and maintenance. The data will be analyzed in the ship to identify a faulty part and notify the ship owner of the faulty part via the Internet.

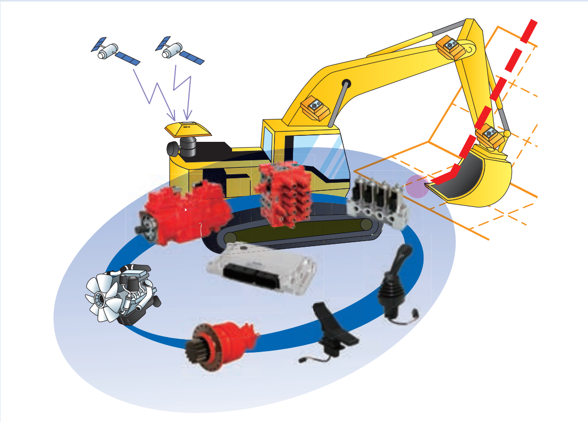
This shift is even taking place in the industrial equipment industry as well where ICT and IoT technologies are not commonly used. N-ECST, the controller for ECO SERVO, whose development began in 2015, is a system that enables remote control and data collection via the Internet. Applying these technologies to equipment used in hydraulic units makes it possible to monitor the condition, communication, and control necessary for maintenance with the condition monitoring function (**Fig. 9**).

## Conclusion

In the medium-term business plan "FY2019 MTBP", the Precision Machinery Business Division is aiming to more than double its consolidated sales from fiscal 2018 by fiscal 2030. To achieve this goal, we will be promoting the development and sales expansion of products and at the same time creating new products and businesses with synergy of the precision machinery business and robot business.

† 7 The KGPR65D, a hydrogen regulator with high-precision gas control, contributes to achieving zero $CO_2$ emissions of running fuel cell vehicles (FCVs).

# Development of Systems for ICT Hydraulic Excavators That Enable the Realization of Computer-Aided Construction



*The demand for ICT construction machinery is increasing as it enables the realization of highly efficient and highly accurate computer-aided construction with ICT (Information Communication Technology) and IoT (Internet of Things) technology for enhanced productivity at construction sites. Leveraging its expertise as a hydraulic equipment manufacturer, Kawasaki is developing hydraulic systems and machine control technologies that can achieve a good balance between control accuracy and operating speed in ICT hydraulic excavator systems. For future systems, Kawasaki is also working toward automation and autonomy with the focus on innovative hydraulic systems.*

## Introduction

Because of the increasingly serious labor shortage at construction sites due to a shrinking labor force of experienced workers, computer-aided construction is increasingly adopted to enhance productivity.

In Japan, the national government has been promoting i-Construction, which is a new framework aimed at enhancing productivity at construction sites, since 2016, and there is an increasingly interest in computer-aided construction.

## 1 Background

Construction processes consist of survey, design, construction, supervision, inspection, and maintenance. Computer-aided construction focuses on the construction process, using ICT and IoT technology to achieve highly efficient and accurate construction. In addition, electronic data obtained through construction are used for other processes for enhancing productivity and ensuring quality throughout all the construction processes. Recently, the demand for ICT construction machinery, which is the tool for realizing computer-aided construction, is increasing rapidly.

## 2 ICT construction machinery

ICT construction machinery incorporates machine guidance technology, which displays on the monitor the difference between the current position of construction machinery estimated with the global navigation satellite system and vehicle sensors and the target value for construction, and machine control technology, which automatically controls construction machinery in real time to minimize the difference between the current position and target value, both of which construction machinery manufacturers are developing. Today, machine control technology, which assists the operator in performing grading work, has already been put on the market and is becoming common. This technology was first adopted for bulldozers, which are mainly used for grading work, and is now being adopted for hydraulic excavators, which are used for many different kinds of work. Kawasaki is focusing on researching and developing ICT hydraulic excavator systems, for which it is difficult to adopt machine control technology, as it provides an opportunity for Kawasaki to leverage its strength.

The main role of ICT hydraulic excavator systems is to control the movement of each axis of the boom, arm, and bucket making up the hydraulic excavator attachment so that the bucket tip follows the desired trajectory. ICT hydraulic excavator systems consist mainly of a hydraulic system, which controls the movement of each axis with hydraulic cylinders as shown in **Fig. 1**, and machine control technology, which estimates the posture based on information from the angle sensors arranged on the attachment to control the bucket tip position.

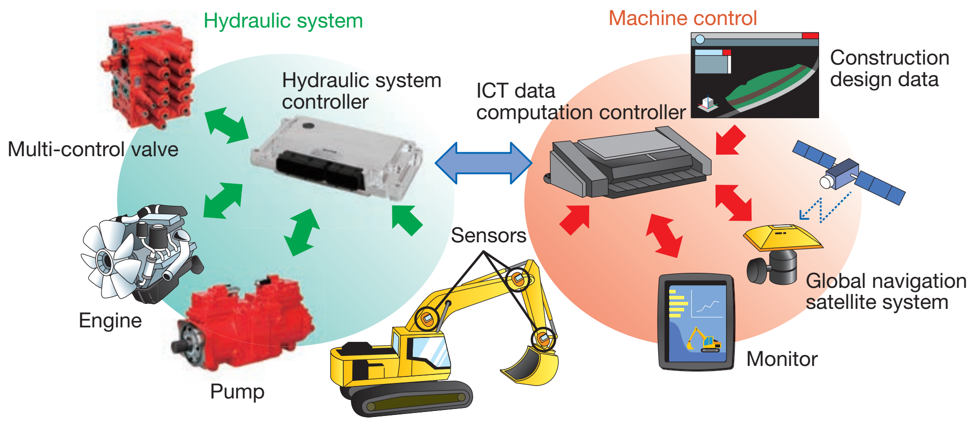



**Fig. 1 System configuration of ICT construction machinery (hydraulic excavator)**

## 3 Development goal and policy

For differentiation from competitors, using hydraulic components and hydraulic controls, which are our strengths, is essential, and we decided to develop optimal hydraulic components and machine control technology for ICT hydraulic excavator systems with "high accuracy, high efficiency, and low fuel-consumption" as our key words. One of our goals is to strengthen our ability to propose systems to customers and offer value-added products through these developments.

We have been developing products for hydraulic components used in conventional hydraulic systems for the purpose of reducing fuel consumption and enhancing efficiency. Therefore, multi-control valves, which play a core role in controlling hydraulic components, are developed with a focus on reducing pressure loss and increasing actuator speed. However, ICT hydraulic excavator systems are required to have high accuracy, as it is important to minimize errors between the target and actual values in construction, so it is difficult to meet the requirements with the conventional hydraulic component characteristics and hydraulic circuit configuration.

That is why we decided to develop a hydraulic system that achieves a good balance between accuracy and speed by improving the characteristics and circuit configuration of hydraulic components — mainly multi-control valves. In addition, we decided to develop our own machine control technology by optimizing the component characteristics and configuration and using robot control technology, which is excellent for having the trajectory follow the target value for construction so as to overcome differences in hydraulic system control between conventional hydraulic systems and ICT hydraulic excavator systems.

## 4 Technical challenges

Trajectory tracking is adopted as a basic function for industrial robots and is widely used in industrial fields, including automotive assembly lines and semiconductor production equipment. However, to achieve the same control for hydraulic excavator attachments the following must be taken into consideration.

- Non-linearity: Control is affected by hydraulic oil compressibility and leak flow rate.
- Self-weight: The size and weight of the attachment are much larger than general industrial robots.
- Delay in response: Actuators are driven via the hydraulic oil discharged from the hydraulic pump.

① Compensation for non-linearity

Hydraulic systems, in which hydraulic cylinders are driven, have strong non-linearity attributable to hydraulic characteristics, such as compressibility, leak flow rate, and hysteresis. To enhance the ability to track a trajectory, the speed of each axis needs to be controlled in an accurate and responsive manner, but the non-linearity is an obstacle to achieving this.

In addition, hydraulic excavators extend their heavy attachment forward and stand on unstable surfaces, and so do not always have a balanced weight configuration. Therefore, minor factors, such as rapid attachment acceleration or deceleration, cause body vibration.

Regardless of body size, even slight vibration causes a large displacement in the bucket tip position, so reducing body vibration is vital to achieving precise construction. However, if the controllability of each axis deteriorates due to non-linearity, the manipulated variable increases accordingly, inducing body vibration.

For this reason, compensating for non-linearity is necessary to achieve high body stability and trackability.

② Compensation for self-weight

Industrial robots compensate for the torque of each axis based on the dynamic calculation results to compensate for the effect of their own weight, thereby improving trajectory trackability. Hydraulic excavators have heavy, large attachments, and so are more greatly affected by their own weight. In addition, hydraulic cylinders have non-linearity specific to hydraulic components, so their torque cannot be controlled as precisely as the torque of electric motors used in robots. Hydraulic excavators are configured so that hydraulic oil is supplied to multiple actuators from one oil pressure source. When multiple axes operate in conjunction with one another, compensating for individual axes requires controlling hydraulic oil allocation precisely. Therefore, the gravity compensation for industrial robots cannot be applied, and compensation specifically for hydraulic systems is required.

③ Compensation for delayed response

Industrial robots have their axes driven directly by electric motors but hydraulic excavators have their actuators driven via hydraulic oil discharged from hydraulic pumps, causing a relatively large delay in response.

For conventional hydraulic excavators, this response delay is compensated for by the operator based on their experience. For example, in grading work, the boom is moved up and down in conjunction with the movement of the arm, but the operator knows from their experience that at the start of operation, it is too late to operate the boom after confirming the arm operation and operates the boom and arm almost at the same time.

Machine control technology requires the ability to track various trajectories and high responsiveness like experienced operators have, so delays in response needs to be compensated for.

## 5 Efforts we have made so far

**(1) Development of hydraulic systems**

Compensation for non-linearity: Hydraulic systems use their own weight as energy to return some of the hydraulic oil at the outlet to the inlet, thereby achieving a good balance between high-speed operation and high energy efficiency. At this time, the amount of hydraulic oil returned to the cylinder inlet (the regeneration flow rate) changes depending on the posture and load, which is a major cause of non-linearity.

Therefore, we established the technology to accurately estimate the regeneration flow rate by using the pressure sensor on the cylinder, thereby achieving improved controllability with speed control that takes the regeneration flow rate into account. **Figure 2** shows the configuration of the regeneration section of the hydraulic circuit. **Figure 3** shows a schematic of the regeneration flow rate estimation logic.

The regeneration flow rate is estimated based on the pressure sensor value of the cylinder and the estimated opening values of the regeneration valve and regeneration cut valve. At this time, the estimation accuracy of the control flow rate of the regeneration valve is important. We adopted a new calculation method, thereby achieving improved estimation accuracy.

For stable, efficient operation of the cylinder, it is important to balance the flow rates at the inlet and outlet of the cylinder. With the developed method, this balance can be maintained, even when the regeneration flow rate changes, by compensating for the cylinder inlet flow rate based on the estimated regeneration flow rate.

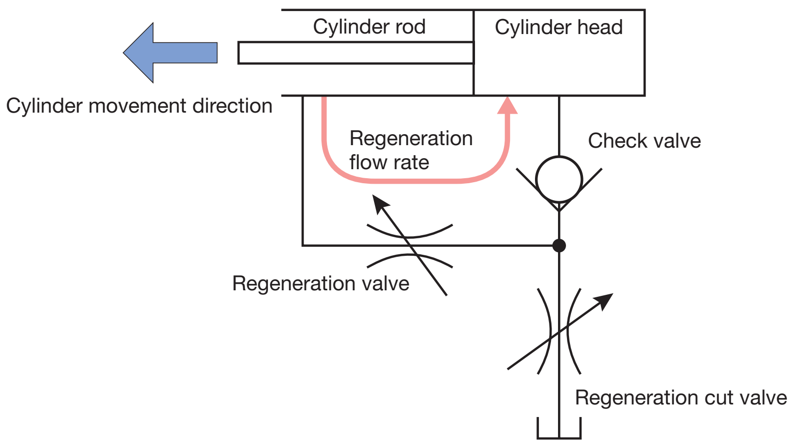



**Fig. 2 Hydraulic circuit configuration (regeneration section)**

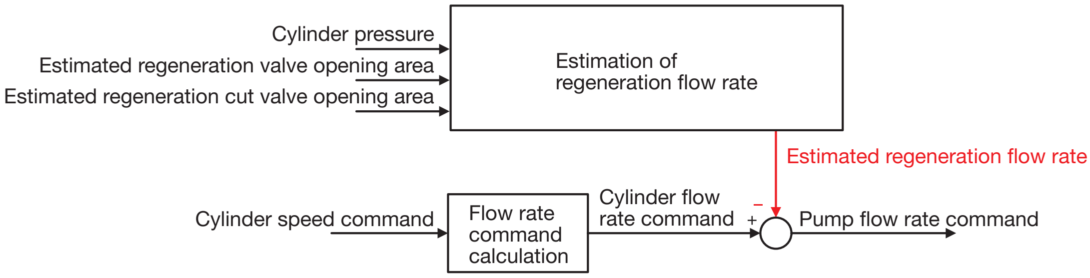



**Fig. 3 Estimation logic for regeneration flow rate**

This has enabled efficient regeneration and linear cylinder response.

Compensation for self-weight: We developed a gravity compensation method with flow control using an independent metering valve (IMV) and a pressure sensor. The control method with an IMV controls the inlet passage meter-in MI and outlet passage meter-out MO individually and optimally controls the MI and MO according to the operating state, thereby providing improved controllability of cylinder speed. This control method has higher flexibility than conventional control methods.

The gravitational action on the link mainly influences the MO-side cylinder pressure. Gravity compensation is given with precise MO control that uses the characteristics of the IMV and accounts for cylinder pressure.

The target speed of each axis is converted to the target flow rate for the MO. The required opening area is calculated based on the target flow rate and the differential pressure of the MO valve obtained from the cylinder pressure sensor. The MO valve is electronically controlled so that the actual opening area follows the required opening area, thereby allowing the cylinder speed to precisely follow the target value. At this time, compensation is applied to the electronic control of the valve, including valve characteristics, thereby achieving higher and more stable control accuracy. Such precise control of the MO of each axis has made it possible to compensate for the effect of gravity and at the same time optimize hydraulic oil allocation at the time of complex operation, thereby enabling independent control of each axis even in hydraulic systems using the same hydraulic oil source for different axes.

This has achieved gravity compensation that can mitigate the effects of posture and load on hydraulic systems.

### (2) Development of machine control technology

The automatic grading assist control is a machine control technology and automatically moves the boom up in relation to the movement of the arm when the bucket tip is about to dig deeper than the target leveled ground surface by the operator's operation as shown in **Fig. 4**.

Also, this control automatically moves the boom down when the bucket tip is about to move away from the target leveled ground surface. To achieve such operations, the controller constantly calculates the postures of the

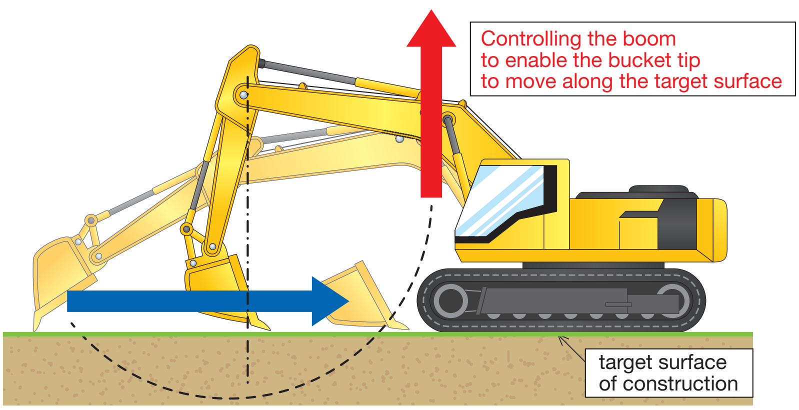



**Fig. 4 Machine control technology (automatic grading assist control)**

hydraulic excavator and attachment based on sensor information.

To accurately move the arm, boom, and bucket of a hydraulic excavator, the hydraulic oil from the hydraulic pump is discharged at the optimal flow rate and is allocated optimally to each actuator by the multi-control valve.

To accurately move the arm, boom, and bucket of a hydraulic excavator, the hydraulic pump discharges the hydraulic oil at the optimal flow rate and the multi-control valve controls the flow rate optimally to each actuator.

In addition, position feedback control is performed so that the bucket tip position calculated based on the signals from the sensors installed on the attachment follows the target leveled ground surface.

Compensation for delayed response: As shown in **Fig. 5**, with the attachment extended, the boom moves up more than the operator's operation calls for. When the arm is nearly vertical to the ground, the amount of upward boom movement is smaller.

At this time, if the control gain for the boom is constant with the attachment extended, the boom cannot follow the operation of the arm due to the delayed response, resulting in the tip digging in too much. When the arm is nearly vertical to the ground, boom operation is more sensitive to arm operation, causing hunting due to the delayed response. To solve this problem, we adopted a control for compensating for the manipulated variable of the boom according the posture of the hydraulic excavator. This control has achieved stable, smooth grading work with the attachment operation speed maintained.

## 6 Efforts for future hydraulic excavator systems

Many construction machinery manufacturers and surveying instrument manufacturers have put semi-automatic systems for assisting operators by means of

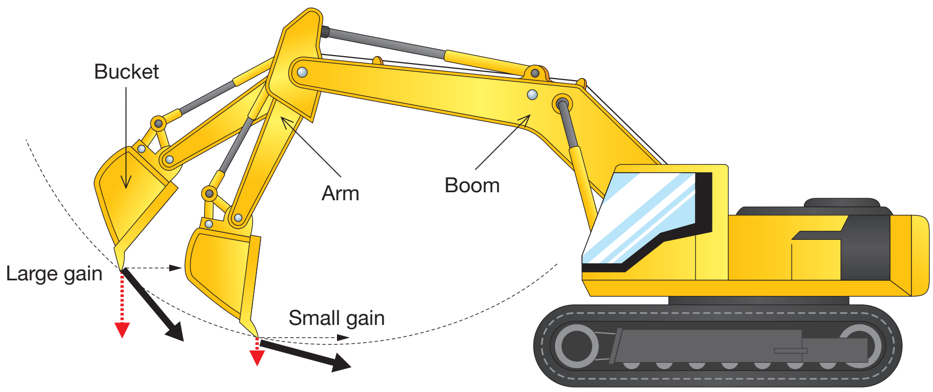



**Fig. 5 Boom control correction based on hydraulic excavator posture**

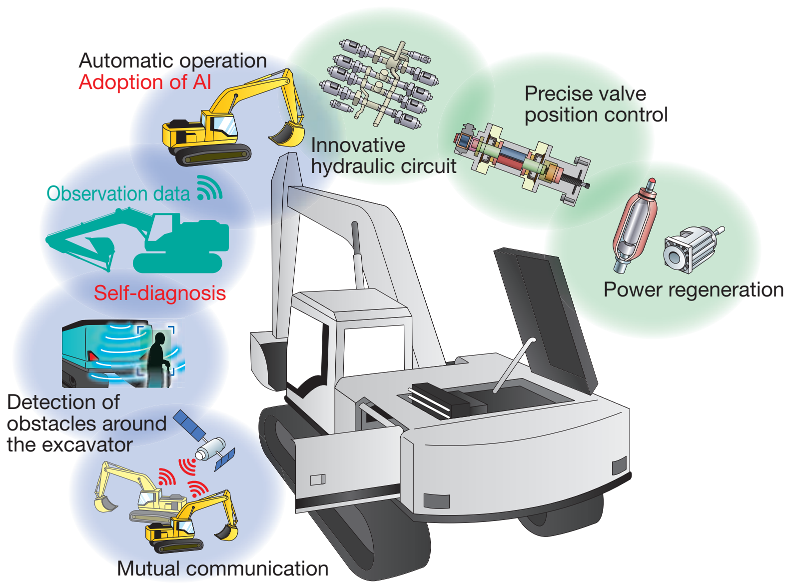



**Fig. 6 Concept of future system**

machine control on the market and are conducting research and development for automation and autonomy as the next step.

Kawasaki is also developing machine control systems with the aim of developing systems that use innovative hydraulic systems at their core and support automation and autonomy. Using hydraulic technology, which is one of Kawasaki's strong points, we are developing innovative hydraulic systems suitable for automation and autonomy as shown in **Fig. 6** for differentiation from competitors.

(i) Innovative hydraulic system

With the aim of enhancing both performance and cost efficiency, we are conducting research and development on hydraulic systems suitable for automation and autonomy. More specifically, we are working to further reduce pressure loss, reduce fuel consumption and enhance operational efficiency with energy regeneration, and achieve a good balance between high maneuverability and high trackability. We are also conducting research on hydraulic components and systems that enable improvement of maneuverability and controllability with precise, linear attachment operation, and further cost efficiency improvement through the integration and elimination of functions, and redesigning of the configuration and structure.

(ii) Automation and autonomy

Taking a comprehensive look at construction sites, research and development are underway on unmanned construction where multiple construction machines are automatically linked with one another. This represents the transformation of construction sites into the equivalent of an automated factory. Kawasaki is conducting research and development on robotizing construction machines by using the technologies it has accumulated for industrial robots. More specifically, Kawasaki is conducting research aimed at realizing ICT hydraulic excavator systems having higher work efficiency and finishing accuracy than experienced operators, including the system for hydraulic excavators themselves to learn autonomously and create optimal operation plans, the system for detecting humans and obstacles around the excavator and adjusting the operation plan, and the system for detecting the soil condition and adjusting the excavation method and pattern.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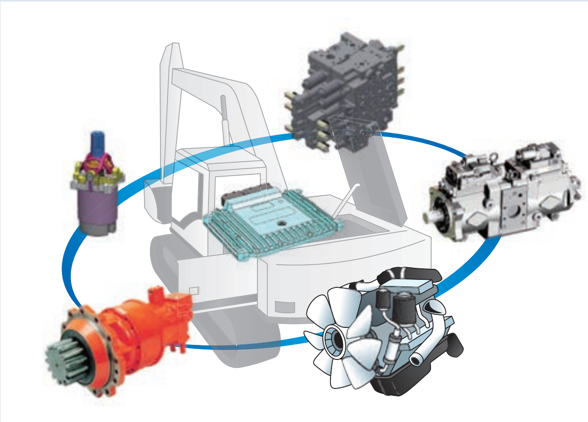
## Conclusion

We are developing the machine control technology for assisting operators as an effort to develop ICT hydraulic excavator systems.

We will be working to further enhance our capabilities of developing ICT hydraulic excavator systems as well as proposing these systems to customers and developing the most suitable components for these systems, thereby contributing to improving the performance and functionality of industrial vehicles, including hydraulic excavators.

# Development of Components for ICT Hydraulic Excavators That Enable the Realization of Computer-Aided Construction



*Recently, a shortage of labor mainly due to the aging of construction workers and resigning of skilled workers is becoming a serious issue at construction sites, and the construction industry is making efforts to boost its efficiency by utilizing i-Construction, which uses ICT (Information and Communication Technology) and IoT (Internet of Things) technology. Kawasaki is developing hydraulic components and control devices for ICT hydraulic excavators equipped with the machine control (semi-automatic and full-automatic) functions that support computer-aided construction.*

## Introduction

Recently, a shortage of labor mainly due to the aging of construction workers, including experienced operators is becoming a serious issue at construction sites. To address this issue, the construction industry is working to boost efficiency and ensure construction quality by utilizing i-Construction, which uses ICT (Information and Communication Technology), IoT (Internet of Things) technology, among other technologies.

## 1 Background

Hydraulic excavators play a central role in many construction sites. Recently, construction machinery manufacturers are developing hydraulic excavators equipped with machine control functions (semi-automation / full automation) that support computer-aided construction, and therefore, electronic motion control is required. Kawasaki is developing electronically controlled hydraulic components as well as electronic control devices that support ICT hydraulic excavators.

## 2 Product development concept

### (1) Hydraulic excavators and computer-aided construction

The actuators, which are used in hydraulic excavators to perform digging, swinging, travelling, and other operations, are connected to the pump via control valves and are operated by using joysticks. Kawasaki's hydraulic components have been adopted for many excavators and are highly evaluated in terms of controllability and reliability[1].

Construction machinery manufacturers, which are Kawasaki's customers, have begun putting ICT hydraulic excavators that support computer-aided construction on the market and have been continuing development aimed at further improving construction efficiency and quality. For example, the bucket, arm, and boom need to be finely operated at the same time to move the bucket linearly for digging, which requires experience and skill. However, ICT hydraulic excavators allow inexperienced operators to achieve the same level of construction quality as experienced operators. In addition, ICT hydraulic excavators can be equipped with additional safety features.

### (2) Required performance

Pumps and control valves to be mounted in ICT hydraulic excavators need to be electronically controlled. These components need to be electronically controlled, not only to convert command signals from the controller to hydraulic signals and operate actuators in an accurate and responsive manner, but also to exert their performance stably under various load conditions. In addition, to achieve high-functionality, high-performance control, the controller is required to have a microcomputer system that can process a large amount of information and calculations for control. Moreover, measures need to be taken for the increased amount of heat generated in the drive circuit, which is required to drive multiple proportional pressure-reducing valves.

At construction sites that do not completely support computer-aided construction, excavators need to be operated with electric joysticks, so the joystick is required to have performance and reliability equivalent to or higher than conventional hydraulic pilot control valves.

## 3 Details of development

**(1) Pumps**

Pumps serve as the heart of a hydraulic system, and so are required to have high efficiency, low noise, and high reliability. In 2015, Kawasaki put the K7V series pump shown in **Fig. 1** on the market, which has significantly enhanced performance and reliability with the latest technologies.

This pump is equipped with proportional pressure-reducing valves in the regulator, which controls the discharge capacity, as electronically controlled pumps are required for ICT hydraulic excavators. With a combination of proportional pressure-reducing valves and control valves, the movements of the hydraulic cylinder and hydraulic motor are finely controlled by accurately controlling the discharge capacity of the pump in response to the command output from the controller, thereby achieving reduced fuel consumption with an optimally reduced discharge flow rate.

Currently, construction machinery manufacturers are conducting model-based development from the prototyping and evaluation stage in developing increasingly complicated systems. Kawasaki is offering the pump simulation model it developed based on its advanced simulation technology and abundant experimental data to construction machinery manufacturers, thereby contributing to their front-loading development for ICT hydraulic excavators and other machinery.

In the future, the function of monitoring the status of each hydraulic component will become more important as ICT hydraulic excavators are adopted more with more sophisticated machine control. Kawasaki is developing sensors and monitoring technologies that enable stable and accurate detection of the pump status even under harsh conditions specific to construction machinery, including high temperature, with the aim of meeting various future needs, including failure detection.

**(2) Control valves**

Control valves for excavators are multi control valves that comprehensively control the movement of excavators as shown in **Fig. 2**. In response to the pressure command from the hydraulic pilot control valve, the internal spools of the control valve move to switch the oil passage so that the hydraulic oil discharged from the pump is distributed to the hydraulic motors for travelling and swinging and the cylinders used mainly to drive the boom, arm, and bucket. In addition, the control valve adjusts the opening of the oil passage according to the displacement of the spool to adjust the speed of each actuator, and therefore is required to have high controllability to achieve the intended excavator movements, including very low speed operation and simultaneous operation of multiple actuators.

ICT hydraulic excavators are intended mainly for automation, maneuverability improvement, and fuel consumption reduction. To achieve these, the control valve is required to have electronic control and higher controllability, so we installed the proportional pressure-reducing valves described later on the control valve so that the spool and internal parts, which had been driven by a conventional hydraulic pilot valve, could be driven by the proportional pressure-reducing valves as shown in **Fig. 3**. However, we encountered several technical challenges. For example, (1) ensuring the response-level of equal to or higher than that of conventional control valves, and (2) installing about 20 proportional pressure-reducing valves per control valve and providing primary pressure lines and drain passages for all the proportional pressure-reducing valves. To address these challenges, we designed the control valve so that the oil passages at the upstream and

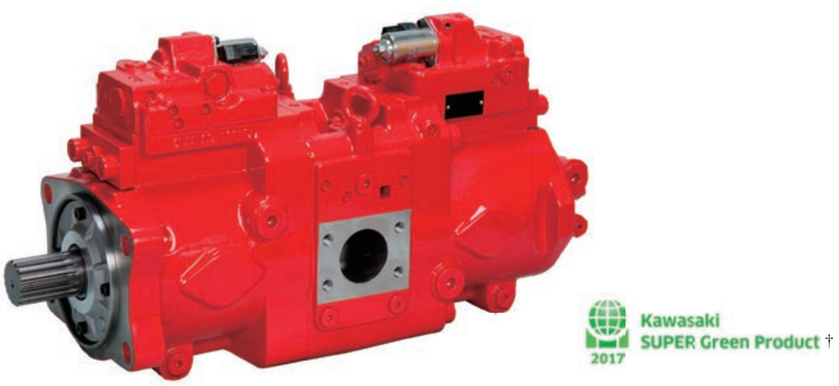



**Fig. 1 Pump for excavators K7V125DTP**

† The K7V Series, a high-efficiency, low-noise, compact, and high-reliability hydraulic pump, has been widely used for construction machinery (mainly excavators).

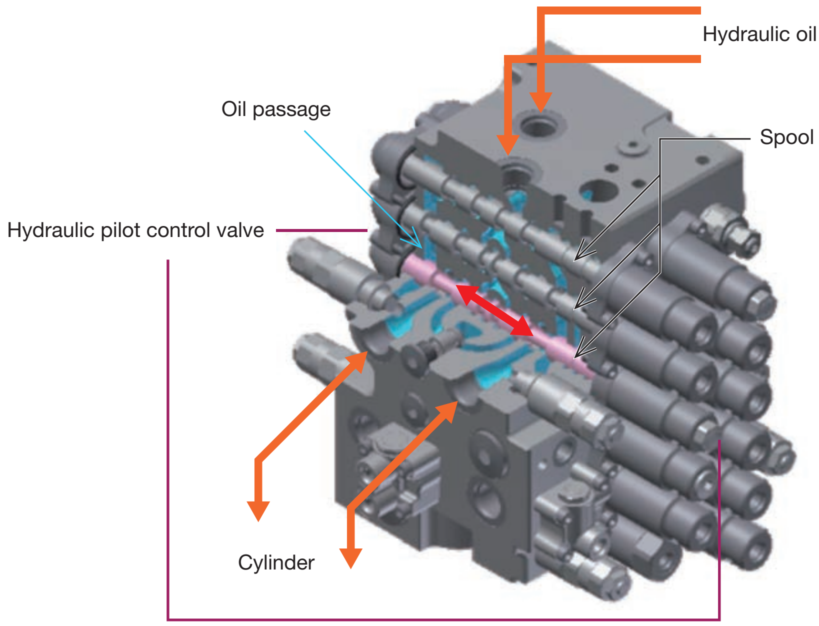



Fig. 2 Control valve for excavators

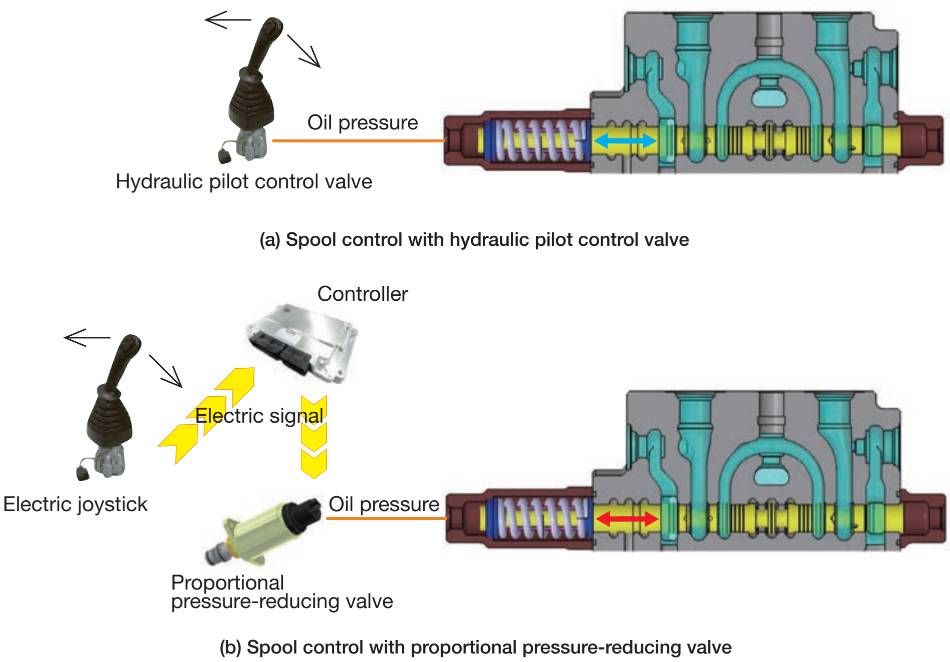



Fig. 3 Spool control types

downstream ends of the proportional pressure-reducing valves have shorter lengths, while having the minimum required area for maintaining the responsiveness, so as to allow air to bleed easily from the oil passages and achieve cost reduction with a compact layout.

We have already developed new models of control valves equipped with proportional pressure-reducing valves by installing proportional pressure-reducing valves on conventional control valves for mid- and large-sized excavators.

The models currently under development use conventional control valves driven by hydraulic pilot control valves as the base model, but we will develop optimal, dedicated valves for electronic control.

### (3) Cartridge type proportional pressure-reducing valve

Cartridge type proportional pressure-reducing valves output control pressure proportional to the current command value and are installed directly into the control valve to control the stroke of the spool. Cartridge type proportional pressure-reducing valves are a key component because they affect the performance of the control valve and are required to have high controllability. Multiple proportional pressure-reducing valves are installed into one control valve and if any of them fail, the excavator will no longer work. Therefore, cartridge type proportional pressure-reducing valves are required to have high reliability and durability and not to fail even after prolonged use in harsh conditions.

In computer-aided construction, excavators are automatically controlled, and therefore, the performance of proportional pressure-reducing valves, which control the control valve, is important. We made improvements to optimize the magnetic circuit design of the solenoid and reduce the friction coefficient of each sliding part, thereby reducing hysteresis and variations in output characteristics and enhancing reproducibility as shown in **Fig. 4**.

Many failures in proportional pressure-reducing valves are caused by a broken solenoid coil due to water intrusion or a stuck spool due to contaminated hydraulic oil. To prevent broken coils, we improved the material and waterproof structure of the solenoid coil molding to achieve excellent waterproof properties. To prevent contamination, we installed a filter outside the valve so that contaminants do not reach the sliding portion of the spool. In addition, not to affect the passage design of the control valve, we developed a specially designed, extremely thin filter shown in **Fig. 5**.

### (4) Controller

The machine control used in ICT hydraulic excavators and other construction machinery, which electronically controls excavators, provides improved maneuverability and safety and reduced fuel consumption. To achieve such machine control, the controller is required to elicit the maximum performance of each hydraulic component and control the excavator to achieve complicated movements. Therefore, the controller is required to have the ability to process a large amount of information and logic related to control and communication, such as input signals from the sensors and switches, and output signals to the proportional pressure-reducing valves and solenoid-operated directional control valves. Consequently, we adopted the dual microcomputer system shown in **Fig. 6**.

This system uses two microcomputers for input/output

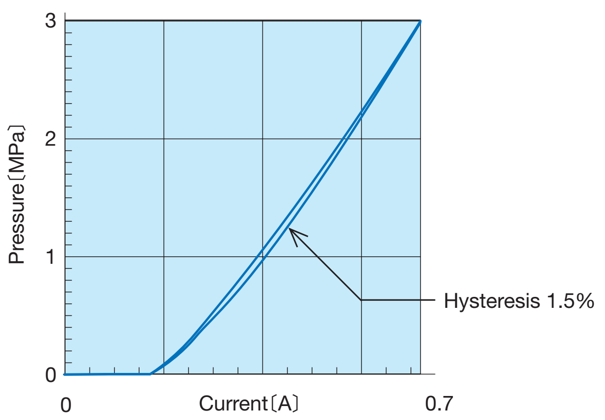



**Fig. 4 Reduction of hysteresis (representative characteristic)**


**Fig. 5 Appearance of cartridge type proportional pressure-reducing valve**

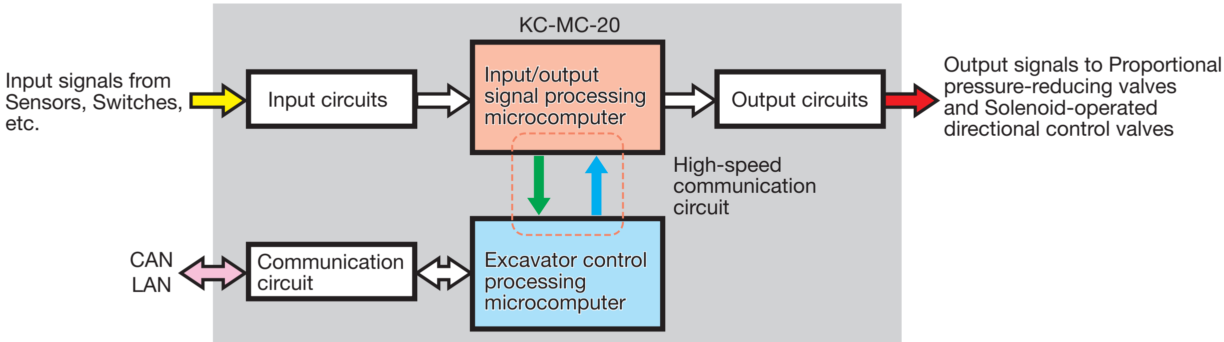
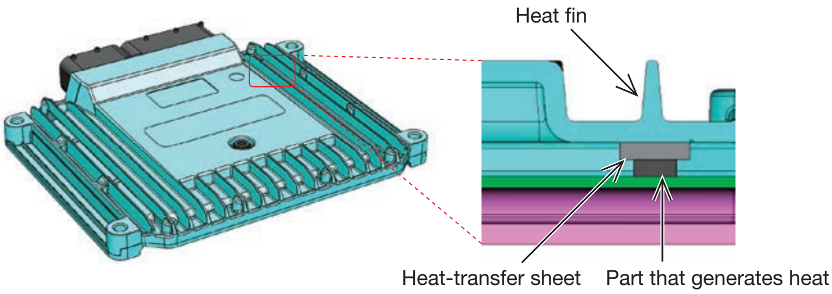


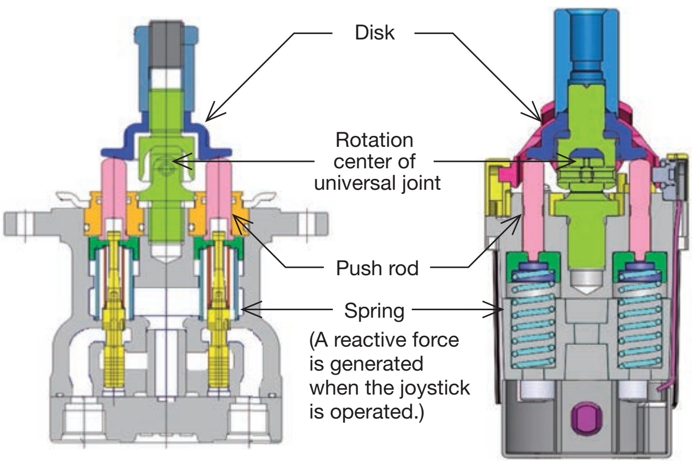

**Fig. 6 Dual microcomputer system**




(a) Appearance (b) Sectional view

Fig. 7 Heat dissipation structure of case


Fig. 8 Appearance of electric joystick ERU2-7.0




(a) Hydraulic pilot control valve (b) Electric joystick

Fig. 9 Comparing lever return mechanisms



†† ERU2-7.0, an electric joystick used for operating construction machinery, has significantly reduced power consumption and best-in-class durability at the same time.

signal processing, excavator control processing, and communication processing, which have conventionally been done by one microcomputer. This system facilitates control program creation and prevents the microcomputer from exceeding its processing capacity due to increased throughput. In addition, the two microcomputers are connected with a high-speed communication circuit so that they can operate in cooperation with each other.

The controller drives multiple proportional pressure-reducing valves. Heat generation of the electronic circuits due to the proportional pressure-reducing valves drive, deteriorates electronic parts, resulting in reduced service life or failure. For this reason, the controller is required to have a circuit board that generates less heat and is designed to have a structure that efficiently conducts heat from the board to the case.

Therefore, we newly designed a low heat generation circuit to reduce heat sources and adopted a structure that conducts heat from the board-mounted components, which are sources of heat, to the case and radiates the heat from the heat fins on the case shown in **Fig. 7**.

### (5) Electric joystick

We adopted a structure that couples the lever and angle sensor by means of sliding coupling to detect the tilt angle. The electric joystick is designed so that the joystick returns to the neutral position by spring action when the operator releases his or her hand as shown in **Fig. 8**. Its structure and components incorporate various design know-how so that they can withstand use in harsh conditions.

(i) Lever return structure

Kawasaki has maintained the top share in the field of hydraulic pilot control valves for conventional excavators for over 30 years. The electric joystick has the lever return structure shown in **Fig. 9**, inheriting excellent maneuverability, reliability, and durability from the previous models.

(ii) Angle sensor

The angle sensor, which converts the operating angle of the lever to electrical signals and is one of the most important parts, is required to have high reliability. Therefore, we adopted a non-contact structure using a hall-effect sensor and a sealing structure, thereby achieving high durability and excellent waterproof properties. In addition, we optimized the electronic circuit including sensors, thereby achieving excellent immunity to noise.

(iii) Size reduction

Electric joysticks are required to be small, but if the size is reduced too much, the strength may decrease, resulting in poor durability or reliability. Therefore, we optimized the design specifications, thereby achieving size reduction with durability and reliability equivalent to or higher than conventional hydraulic remote control valves.

## Conclusion

The number of excavators and other construction machines that support computer-aided construction is increasing, and the construction methods used at construction sites are changing accordingly.

In addition to the components we developed this time, we will be developing optimal products for future advanced excavators by combining hydraulic technology and electronic control technology.

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# Development of a Hydraulic System for Large Press Machines


*While the aircraft demand is expected to increase in the aircraft industry, and cutting-edge large press machines have been developed and deployed with the purpose of domestically producing large forged parts mainly for aircraft and power plants. Amid such a situation, Japan Aeroforge, Ltd. began operating a large press machine in April 2013.*

*Kawasaki was in charge of developing a hydraulic system, which constitutes the core part of the machine, and developed a hydraulic system having unprecedented high pressure and large flow rate and a high-pressure, large-capacity pump, which that serves as a drive source for the hydraulic system.*

## Introduction

Amid the current globalization, the commercial aircraft market forecast says that the demand for aircraft, which is driven mainly by the Middle East and Asia-Pacific region, is expected to increase about 2.4 times in the next 20 years, and the number of jetliners in service is expected to double accordingly.

## 1 Background

Large forging presses owned by domestic forging manufacturers are used mainly for manufacturing pressure vessels for nuclear power generation as well as power generation turbines and crankshafts. Their maximum power, which represents their press force, is 10,000 to 15,000 tons. However, manufacturing large forged parts for aircraft, which are generally made of titanium and nickel, requires presses with even larger power, which is why the industry has been dependent on only a few overseas forging manufacturers for all these parts. While the demand for aircraft is expected to increase, Japan Aeroforge, Ltd. was established in 2011 with investments by material manufacturers, airframe and engine manufacturers, and trading firms with the purpose of domestically producing large forged parts so the domestic aircraft industry can be more globally competitive, and it was decided to develop a hydraulic forging press with the largest power in the world of 50,000 tons.

In developing the 50,000-ton press, Kawasaki was in charge of establishing a high-pressure, high-flow hydraulic system and developing a high-pressure, large-capacity pump, which serves as the drive source for the hydraulic system.

## 2 Overview of development

The 50,000-ton press is a die forging press for forging titanium, nickel, and other materials that require a large load to deform into complicated shapes along the die mounted on the press slide as shown in **Fig. 1.** Therefore, in addition to a maximum power of 50,000 tons, the following functions are required:

① It must be possible to set a wide range of pressing speeds, from very low to high speed, and to set the optimal pressing speed pattern according to the distortion characteristics of the material and fluidity in the die.

② It must be possible to control the parallelism of the press slide with high accuracy and responsiveness to allow the forging of asymmetric products that put an eccentric load on the slide center.

Until the 50,000-ton press, the largest press Kawasaki had delivered a hydraulic system for a power of 15,000 tons, which means the hydraulic system for the 50,000-ton press had the highest pressure and control flow rate range Kawasaki had ever handled. In addition, the highest level of responsiveness and control accuracy for a large press were required. To meet these requirements, we decided to increase the pressure in the entire system, develop an optimal hydraulic system and control logic, and increase the responsiveness of the hydraulic pump.

Fig. 1  Large forged parts produced with 50,000-ton press

## 3 Development of the hydraulic system

**(1) Increasing the pressure and flow rate**

(i) Increasing the pressure

The pressure specification for the hydraulic system was 45 MPa, far higher than the highest pressure for the hydraulic systems for presses Kawasaki had delivered up to that point at 35 MPa. Therefore, it was essential to increase the pressure in the hydraulic equipment including the hydraulic pump as well as the manifolds and joints forming oil passages. The large manifold shown in **Fig. 2** has a maximum weight of over 8 tons and was the largest in number and total weight but we were able to reduce its size while maintaining its strength even at 45 MPa by using FEM analysis to design optimal oil passages.

For the final engine performance, we port matched the intake and exhaust parts and achieved torque characteristics that have a wide power band with a flat torque curve as shown in **Fig. 3** and can easily be handled by the rider.

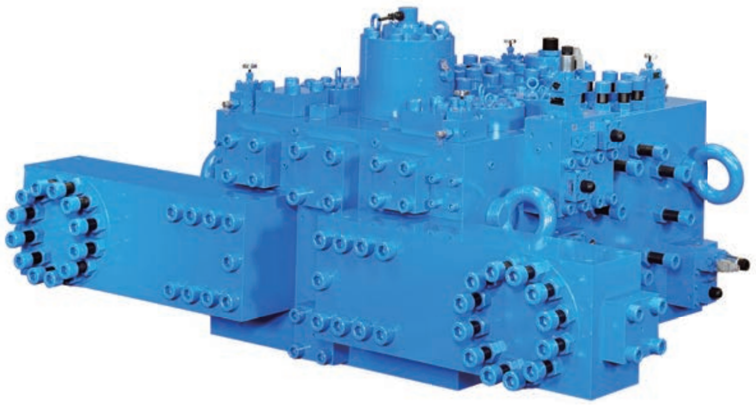

Fig. 2  Large manifold

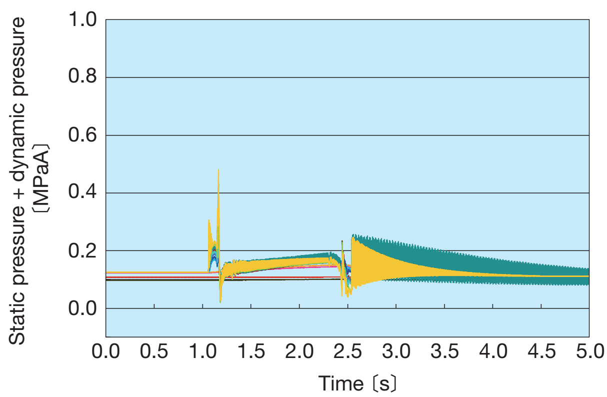


Fig. 3  Example of analyzing return piping pressure with buffer tank

(ii) High flow control

Large hydraulic systems have a large piping length, and a kind of shock called "oil hammering" is expected to occur in the return piping to the tank if the flow rate changes rapidly when the pressing speed increases or decreases or when reversing the direction of operation. Oil hammering may cause the press to vibrate and can damage the piping. Therefore, shock absorbers (small oil tanks sealed with nitrogen gas) were arranged to mitigate oil hammering. By conducting fluid analysis on the tank return piping as shown in **Fig. 3,** we verified how the pressure behaves and studied the optimal layout of the shock absorbers.

**(2) Pressing speed control**

A wide range of pressing speeds, from very low speed to high speed, is required, so the flow rate in the hydraulic system needs to be controlled in a wide range from 1-2 L/min to 10,000 L/min. In addition, in order to achieve the optimal pressing speed according to the distortion characteristics of the material and fluidity in the die, this ultra-large press with a power of 50,000 tons is required to have the same level of responsiveness and controllability as small and medium presses. To achieve this, the hydraulic pump, which controls the pressing speed, is required to have a high-capacity, high-responsiveness, high-accuracy flow control function. To achieve pressing speeds in the range of the minimum flow rate of 1 to 2 L/min, we adopted ECO SERVO, which controls the pump discharge flow rate with speed control using a servo motor, exclusively for the very low speed region.

**(3) Parallelism control**

The press slide is subject to eccentric loads depending on the shapes of the material and die and fluidity in the die. Therefore, the slide table must be kept parallel to achieve the designed shape of the forged part, protect the press, and reduce the number of heating cycles.

For parallelism control, we adopted a control method in which the pressures of the four return cylinders arranged on the press slide opposite the pressing cylinders are controlled individually. As shown in **Fig. 4,** the slide table is made to tilt when eccentric load Fm acts on it. At this time, return cylinders 1 to 4, arranged on the slide table, generate forces F1 to F4 in the direction opposite to the pressing direction to cancel the eccentric load and keep the slide table parallel. The parallelism control capability is determined by the sum of the opposing forces, and so was designed to be equivalent to the weight of the moving parts of the press so as to ensure a maximum pressing force of 50,000 tons.

**(4) Hydraulic system evaluation test**

We developed a new hydraulic system by applying the previously mentioned measures and controls and mounting the newly developed pump described below. Each piece of hydraulic equipment has specifications that satisfy the service conditions of the 50,000-ton press, and the hydraulic circuits and hydraulic units were designed based on Kawasaki's design concept.

However, this hydraulic system was the largest system using the highest pressure we had ever handled, so an unexpected problem causing a system shutdown had the potential to have a substantial impact, including secondary damage. Therefore, we decided to conduct a long-term durability evaluation test under the same conditions as the service conditions of the 50,000-ton press, including the overall configuration of the hydraulic system, hydraulic oil, load, and cycle. The large pump unit shown in **Fig. 5** was installed in the 50,000-ton press. The evaluated unit has the same equipment and circuit configuration as the actual unit with a reduced size. **Figure 6** shows the test data on durability.

We conducted the evaluation test by simulating the actual service conditions of the entire hydraulic system, and identified problems that could not be identified by verifying the specifications of the large pump unit alone or

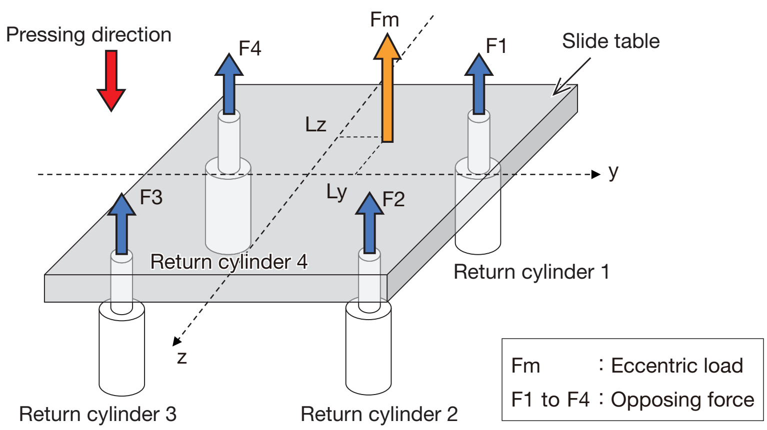


**Fig. 4  Opposing force and eccentric load**

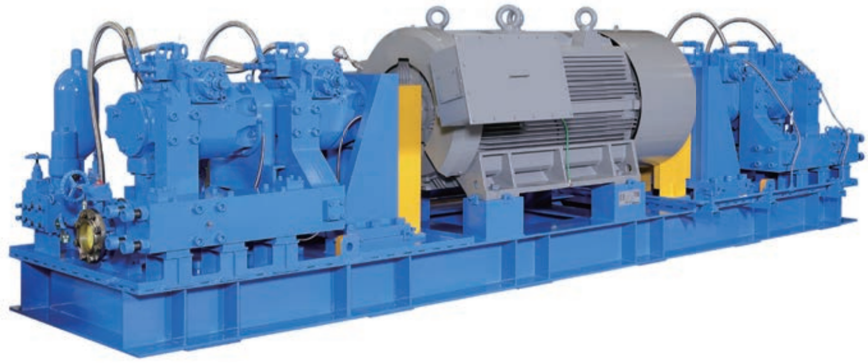

Fig. 5  Delivered large pump unit

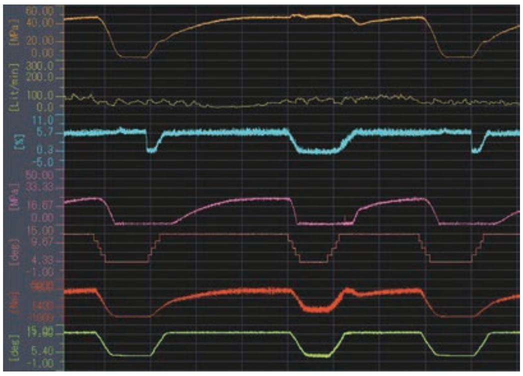


Fig. 6  Simulation test data with actual machine

evaluating the large pump unit alone before delivery. In addition, we were able to verify the reliability of the entire hydraulic system by fixing identified problems with the large pump unit and delivering the large pump unit with a higher degree of refinement.

## 4 Development of a high-pressure, high-flow pump

To satisfy the specifications required for the 50,000-ton press, the hydraulic pump is required to support a high-pressure, high-flow, high-accuracy system. Kawasaki had been offering bent-axis pumps as high-flow pumps, but their rated pressure was 35 MPa, which did not satisfy the required specification of 45 MPa. In addition, bent-axis pumps cannot respond quickly to changes in inclination due to a structural problem. Therefore, we decided to develop a new swash plate pump, which is mainstream in the hydraulic industry as well as in Kawasaki.

**Table 1** shows the specifications of the developed pump. **Figure 7** shows the structure of the developed pump. To increase the responsiveness as mentioned

Table 1  Specifications of pump

| | | |
|---|---|---|
| Model | | K7VG500 |
| Displacement 〔$cm^3$〕 | | 500 |
| Speed 〔$min^{-1}$〕 | Rating | 1, 200 |
| | Max. primping | 1, 350 |
| Discharge pressure 〔MPa〕 | Rating | 45 |
| | Max. | 50 |
| Control method | | Servo valve control method |
| Pump tilt step response | | 0.1 sec or less (0 ⇔ 100%) |

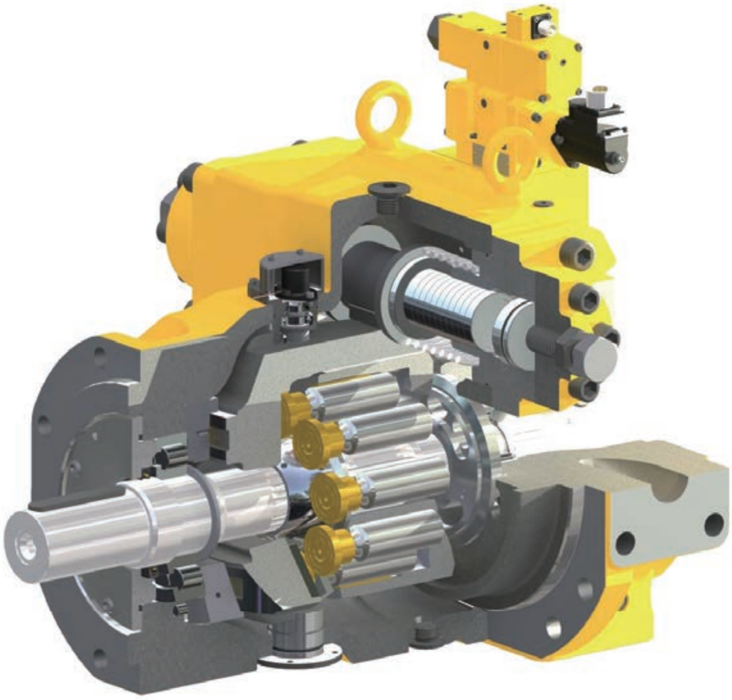

Fig. 7  Construction of pump

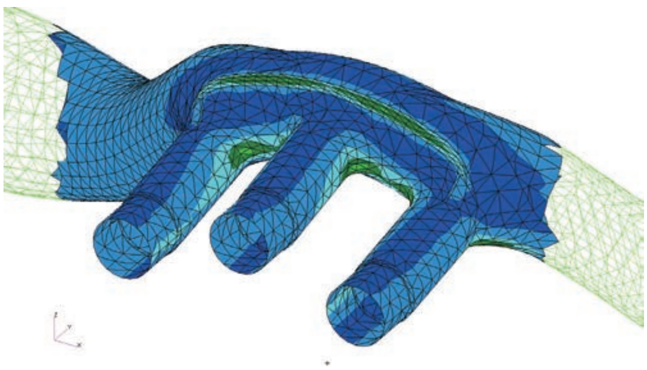

Fig. 8  Example of FEM analysis (stress in valve cover oil passage)

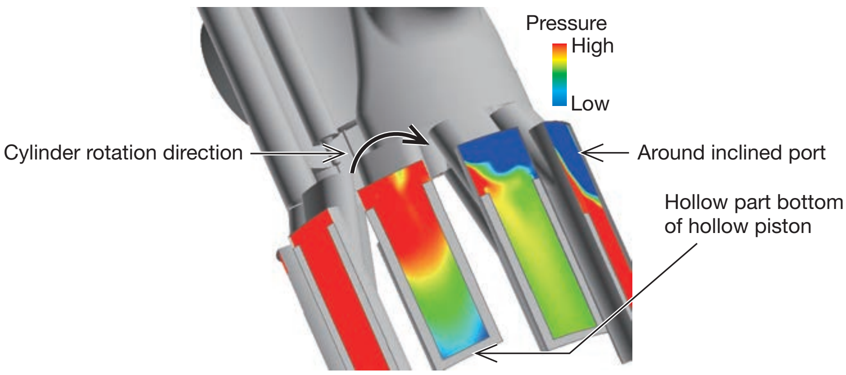


Fig. 9  Example of CFD analysis (pressure in piston and cylinder)

before and increase the pressure, flow rate, and efficiency, we conducted the following developments.

**(1) Increasing the pressure**

For the pump to withstand a rated pressure of 45 MPa, higher strength is required than with the conventional 35 MPa, so we examined both materials and structures. For the rotary part, which is the core part of a pump, Kawasaki has basically been using carbon steel for the cylinder, and copper alloy for the shoe. However, as a result of strength calculations, such as FEM, we decided to use alloy steel for the cylinder and shoe. For the valve covers with pump delivery ports, we initially considered using cast materials in light of workability, but as a result of strength calculations, we decided to use nodular graphite cast iron. We improved the oil passage shape as shown in **Fig. 8,** which is an example of FEM analysis, thereby reducing the stress by approximately 30%.

**(2) Increasing the flow rate**

To increase the flow rate, we set the pump's displacement to 500 $cm^3$ and the rated speed to 1,200 min-1. However, to achieve these numbers, we needed to increase the pump's suction capability. Therefore, using CFD analysis, we minimized the pressure loss even at high flow rates and optimized the oil flow at the suction part, thereby increasing the suction capability. Also, in order to optimize the pressure distribution and flow inside the pump under various operating conditions, including high pressure and high flow rate, we determined the shape by conducting CFD analysis for each section. **Figure 9** shows how the pressure changes in the piston and cylinder while the press is operating. We identified where the pressure dropped and negative pressure was generated, and modified the shape to prevent the generation of negative pressure.

**(3) Improving the efficiency**

Because the pressure and flow rate are high, extremely large energy is required to operate the pump, so it would be better for the pump to have higher efficiency. Therefore, we conducted CFD analysis to reduce the pressure loss in the internal passages and improve leakage inside the pump, and we also conducted simulations to optimize pressure fluctuations inside the pump and minimize loss.

The technology for estimating pump efficiency in the development stage had already been established, and it was applied this time as well. With this technology, the efficiency during operation is estimated based on the specifications of internal parts, characteristic values of hydraulic oil, and temperature increases in the sliding parts.

## Conclusion

The 50,000-ton press has been operating stably since it began operating in April 2013, and Japan Aeroforge, Ltd. began mass-producing airframe parts, landing gear parts, and aircraft engine parts in 2014 after being certified as an aircraft parts manufacturer. In the industrial machinery industry, higher power and higher responsiveness will be required, and so we will be working to develop products that can meet such market needs.

The K7VG500 was developed as a NEDO subsidy program. The authors would like to express their gratitude to all those involved in this program.


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# Development of K3VLS Series Hydraulic Pumps for Use in Construction and Agricultural Equipment


*Kawasaki has developed the new K3VLS series of medium pressure pumps for use in construction and agricultural equipment, which are effectively deployed worldwide. These pumps have achieved customer requirements for both performance and reliability as well as cost reduction, and have been highly rated by customers and applied to various machines.*

## Introduction

Because of global warming, increasing global population, and other social factors, environmental load reduction, automation, high functionality, and various other efforts are required for construction equipment and agricultural equipment, which are vital to our lives in that they play a role in social infrastructure development and food production.

## 1 Background

Regarding hydraulic pumps for excavators as core products in the construction equipment field, Kawasaki has been continuously improving products[1)] while incorporating social and customer needs, thereby increasing its market share in the construction equipment field.

With the aim of becoming a "global-standard" motion control manufacturer for further business expansion, Kawasaki is attempting to make a full-scale entrance into the construction and agricultural equipment (other than excavators) fields.

## 2 Product concept

**Table 1** shows the specifications and needs for hydraulic pumps in both the excavator field and the construction and agricultural equipment field.

The specifications for hydraulic pumps for use in construction and agricultural equipment differ from those for use in excavators, and Kawasaki's hydraulic pumps based on hydraulic pumps for excavators were less competitive than competing products in terms of performance at high speed, cost, and so on.

Table 1 Required specifications and demands for hydraulic pumps

| Item | Excavator | Construction and agricultural equipment (for LS systems) |
|---|---|---|
| Efficiency/reliability | ◎ | ◎ |
| System pressure | ◎ | ○ |
| Controllability | ◎ | ○ |
| Low noise | ◎ | ◎ |
| High speed | ○ | ◎ |
| Space saving | ○ | ◎ |
| Low cost | ◎ | ◎ |

(Note) LS : Load Sensing  Significance of requirement : ◎>○



† The K3VLS Series, a hydraulic pump for mobile machinery with the industry's highest-level pump efficiency and low noise, contributes to improving the fuel consumption of construction machinery.

Therefore, using the technologies we had accumulated for pumps for excavators, Kawasaki decided to develop the K3VLS series of medium pressure pumps that fit the specifications of construction and agricultural equipment, including, in particular, construction and agricultural equipment with a load sensing system.

## 3 Structure and technical challenges of the K3VLS series

### (1) Structure and features of the K3VLS series

**Figure 1** shows the structure of the K3VLS series pump, which was designed to have a simpler structure than Kawasaki's pumps for excavators. With the aim of reducing cost through mass-production technology, with the K3VLS series we were able to reduce the number of parts by 10% and the mass by 20% as compared to the K3VL series, which is Kawasaki's existing pump series for construction and agricultural equipment, by various means such as applying a new assembled piston and shoe with excellent performance and reliability.

The operating principle of the K3VLS series is the same as that of the pump for excavators. The assembled piston and shoe, which rotates with the cylinder block, reciprocates in relation to the cylinder block hole, thereby allowing the pump to continuously suck and discharge hydraulic oil.

### (2) Technical challenges in the development of the K3VLS series

In general, construction and agricultural equipment does not have much space for mounting a pump, so compact, small-displacement pumps are used under high-speed conditions. One of the greatest challenges in developing hydraulic pumps for construction and agricultural equipment is reducing cost while maintaining the same level of performance and reliability as pumps for excavators. To expand our share in the competitive construction and agricultural equipment market, we needed to find solutions to these two conflicting issues.

Therefore, we worked on increasing speed and improving productivity for cost reduction.

## 4 Solutions to technical challenges

### (1) Solution to speed increase

(i) Improving the self-priming capability

When a hydraulic pump rotates at a high speed, the flow rate increases, likely causing cavitation in a hydraulic oil passage. If cavitation occurs in the cylinder block, the effective displacement of the pump decreases, which means that the self-priming capability of the pump decreases. If cavitation appears and disappears repeatedly, the parts may erode. Therefore, cavitation prevention is important in ensuring adequate performance and reliability of hydraulic pumps for construction and agricultural equipment.

To predict the occurrence of cavitation in a hydraulic pump, we improved the simulation technology for the flow of hydraulic oil in a pump as shown in **Fig. 2**. We began studying the shape of the internal passage, which is effective for cavitation prevention, in the design stage, and developed a pump with excellent self-priming capability without having to rework the entire pump.

(ii) Improving rotary stability

Allowing the parts inside a pump to rotate stably at high speed requires an accurate understanding of the various forces acting on each part and the lubrication

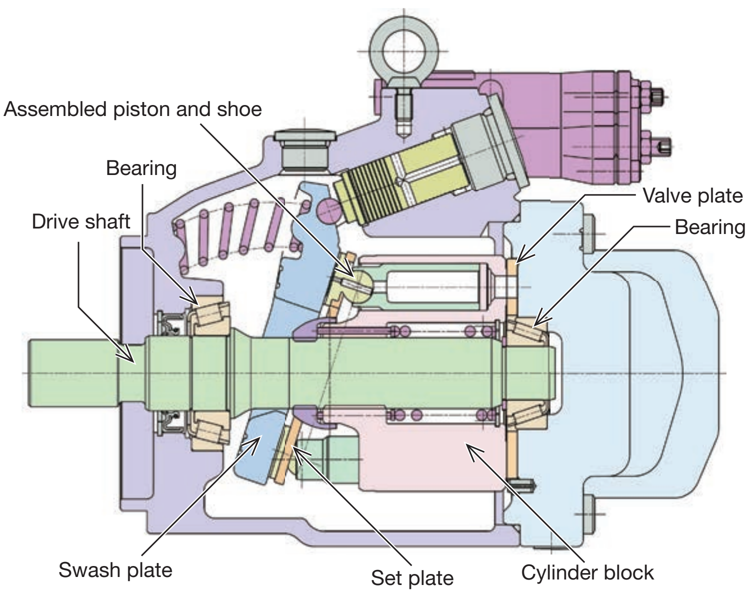



**Fig. 1 Structure of K3VLS series pump**

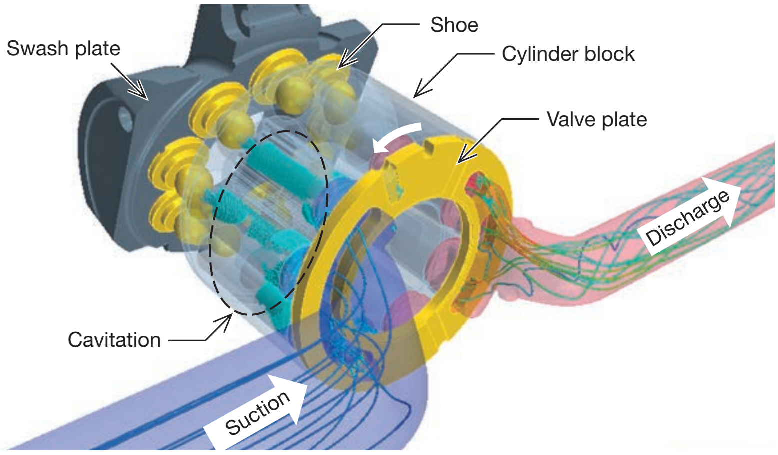



Fig. 2 Fluid dynamics simulation inside the pump

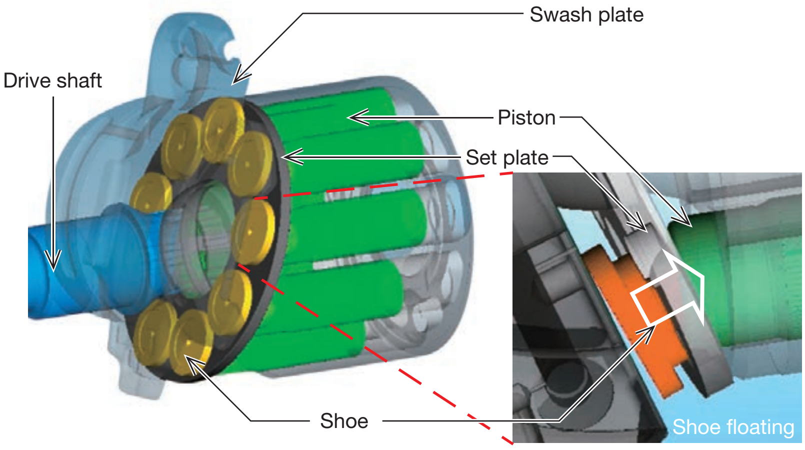



Fig. 3 Multibody dynamics simulation

conditions. However, it is not easy to grasp the characteristics of oil films between parts and various design parameters affect one another in a complicated way; therefore, it is difficult to study these forces and lubrication conditions. To address this, we applied the multibody dynamics simulation technology as shown in **Fig. 3** which takes account of mechanical factors related to the behavior of the parts in the pump, such as contact, deformation, and force by pressure, in the design stage of the K3VLS series.

The behavior of the shoe at high speed is given below as an example. The assembled piston and shoe, which rotates with the cylinder block, is subject to a floating force from the swash plate caused mainly by the inertia force caused by rotation and the viscous force of the hydraulic oil. To prevent shoe floating, which affects performance and reliability, the shoe is mechanically pushed against the swash plate by the set plate. As the speed increases, the floating force acting on the shoe increases, and if the floating force exceeds the pushing force generated by the set plate, the shoe floats from the swash plate.

We studied the floating clearance of the shoe from the swash plate by means of multibody dynamics simulation, and found that the obtained floating clearance was consistent with the measurement result with the actual pump as shown in **Fig. 4**.

This simulation technology was applied in designing the shoe pushing mechanism and studying the optimal shape of the set plate for Kawasaki's hydraulic pumps including the K3VLS series.

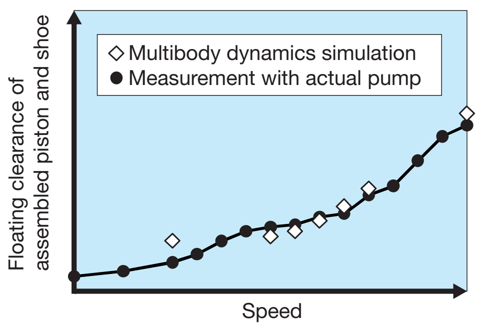



Fig. 4 Simulation results of shoe floating

**(2) Improving the productivity of the assembled piston and shoe (cost reduction)**

(i) Structure of the assembled piston and shoe for the K3VLS series

The assembled piston and shoe for Kawasaki's pumps for excavators has a structure in which the piston has a convex spherical surface and the shoe has a concave spherical surface as shown in **Fig. 5 (a)**. To significantly improve productivity by eliminating the need for machining while maintaining the performance and reliability required for the piston with the required specifications, the K3VLS series adopts an assembled piston and shoe structure where the concave and convex spherical surfaces are reversed as shown in **Fig. 5 (b)**.

This structural change has enabled the application of a new technology aimed at cost reduction through mass production, contributing greatly to the improved productivity of the assembled piston and shoe for the K3VLS series.

(ii) Cold forging of the piston material

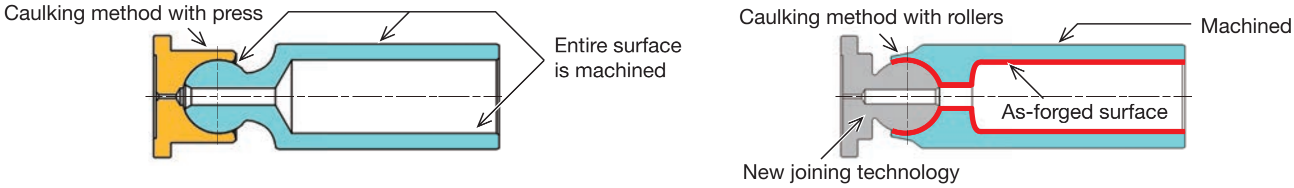
The entire inner surface of the piston for the K3VLS series pump, including the concave spherical surface, is not machined after cold-forging as shown in **Fig. 6**, thereby reducing the total machining time significantly. To ensure the shape and accuracy required for the concave spherical surface of the piston, which slides with the shoe, various cold forging parameters were optimized.

(iii) Method of joining the steel ball and steel plate

To join the round part and plate part of the shoe, we developed a new technique to join the steel ball and steel plate while in contact with each other under pressure as shown in **Fig. 7**. This technique has made it possible to use a commercially available, low-cost, high-precision steel ball as a convex spherical part and eliminate the need for high-precision spherical surface machining and finishing, thereby significantly reducing the machining time.

(iv) Roller caulking

For the assembled piston and shoe for excavators, the




(a) Pump for excavators

(b) K3VLS series pump

**Fig. 5 Structure of assembled piston and shoe**

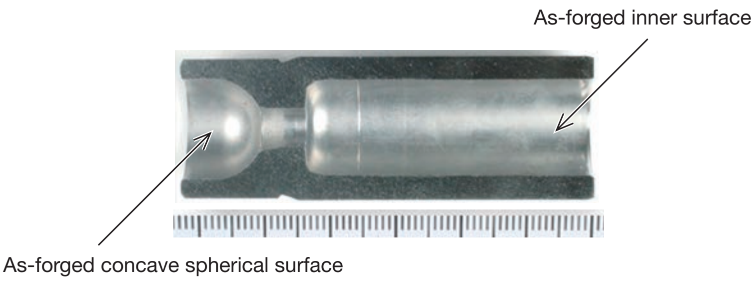



**Fig. 6 High-precision inner surface of forged piston**

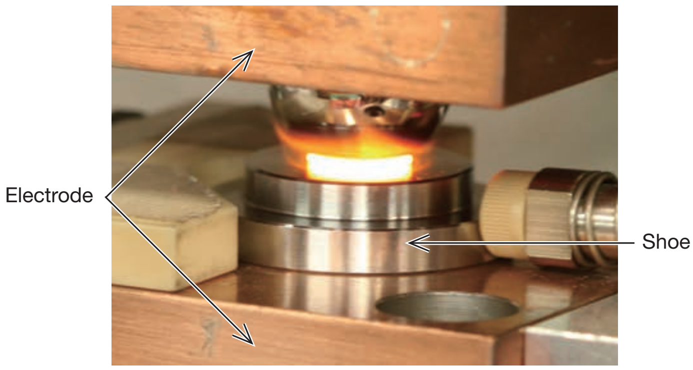



**Fig. 7 New method for bonding steel ball and steel plate**

shoe is caulked to the round part of the piston with a press. For the K3VLS series, the piston is caulked to the shoe using rollers.

As shown in **Fig. 8**, the tip of the piston is plastically deformed with three rollers while being rotated, forming a round joint with the shoe. The precise control of this process has enabled high-precision caulking, contributing greatly to the improved reliability of the assembled piston and shoe.

In addition, this process makes it possible to caulk all types of pistons for the K3VLS series without any setup by precisely controlling the position of each roller. This caulking method has provided significantly improved productivity compared with the conventional caulking method, which requires different press dies for different models.

We began mass-producing the K3VLS85 in April 2015, and now all six models of the K3VLS series shown in **Table 2** are available.

## 5 Future activities

The K3VLS series was designed with the aim of achieving weight reduction and smaller size to meet the required specifications. As an effort to meet the

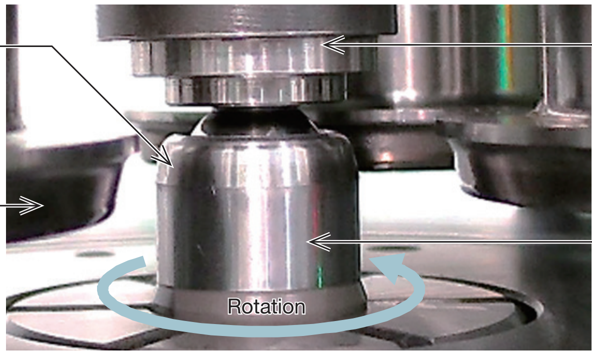
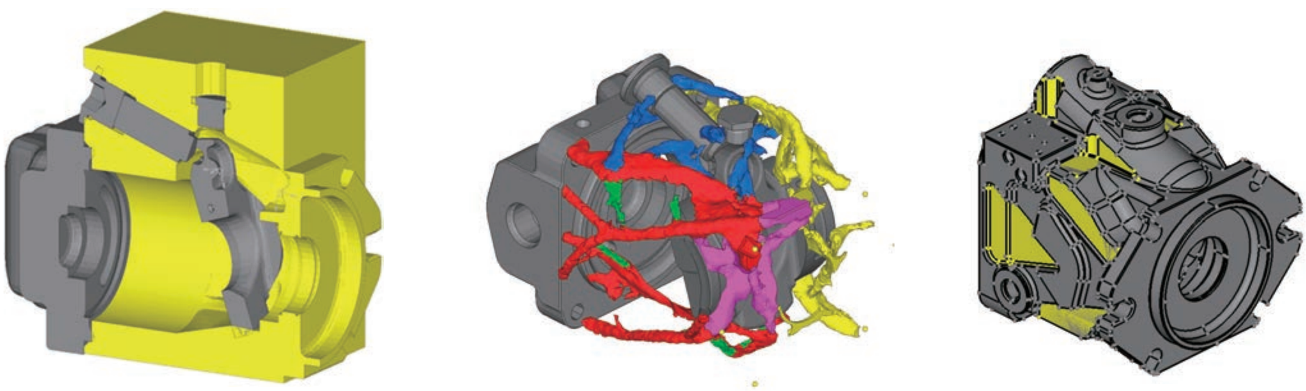



Fig. 8 Joining of piston and shoe by roller caulking

Table 2 Specifications of K3VLS series pump

| Displacement〔cm$^3$〕 | | 50 | 65 | 85 | 105 | 125/150 |
|---|---|---|---|---|---|---|
| Discharge pressure〔MPa〕 | Rating | 28 | | | | |
| | Peak | 35 | | | | |
| Max. self-priming speed〔min$^{-1}$〕 | | 2, 700 | 2, 600 | 2, 500 | 2, 300 | 2, 200 |



(a) Setting of design region　(b) Topology optimization result　(c) Shape determined by engineer

Fig. 9 Weight reduction of casing using structural optimization technology requirement of further weight reduction of construction and agricultural equipment, we are considering applying the structural optimization technology to the pump casing as shown in **Fig. 9**. The optimization method used is topology optimization, which uses the element density of the finite element method (FEM) as a design variable to obtain the optimal density distribution.

With this method, a casing shape with the minimum total mass and optimal stiffness can be obtained by creating a design region where parts can be arranged with an FEM model and specifying the stiffness of each part required for the casing. In addition, the mechanical meanings indicated by the optimization results are analyzed and incorporated into the shape of the casing to which other necessary functions have been added so as to achieve a lightweight, compact, stiff casing.

## Conclusion

Selling over 50,000 units in total, the K3VLS series has been highly evaluated as hydraulic pumps that meet the needs for construction and agricultural equipment, and they have been used in various machines.

We will be working hard to develop products that meets diverse market and customer needs.

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# Development of Electro-hydraulic Actuators for Robots

*The first industrial robot in Japan (Kawasaki-Unimate) was hydraulically actuated, but since the late 1980s, electric motor actuation has been replacing hydraulic actuation. In recent years, however, humanoid robots, which are increasingly expected to be used mainly at disaster sites, need to be durable and powerful, and hydraulic actuation has been recognized once again.*

*Kawasaki is developing Hydro Servo Muscle, which is an electro-hydraulic actuator that is characterized by its high impact resistance and power density and is intended to be applied to the legs of Kaleido, which is a humanoid robot Kawasaki is developing.*

## Introduction

In recent years, there are increasing expectations for life-size humanoid robots, which do various tasks at disaster sites and in extreme environments in place of humans by using tools for humans.

## 1 Background

Hydraulic actuation technology has mainly been used for construction machinery that requires high power and high environment resistance, and electric motor drive technology has been used in the robot field where high speed and high accuracy are required. Recently, however, the trend is to use hydraulic drive for humanoid robots and other robots that require powerful movements in severe environments.

## 2 Humanoid robots

Amid such circumstances, Kawasaki is developing humanoid robots as other manufacturers are. Currently, Kawasaki's humanoid robot has a total height of 1.75 m and a weight of 84 kg, and it has 32 degrees of freedom in total for all the joints, including the legs and arms, driven by electric actuators. Achieving the same size as humans requires pursuing size and weight reduction in each part and eliminating projections that humans do not have to prevent interference in each section. Also, low-speed, high-thrust motion is required for standing up, and high-speed, low-thrust motion is required for walking.

Therefore, actuators for humanoid robots are required to have small size and weight, a good balance between high-speed, low-thrust motion and low-speed, high-thrust motion, high reliability, and high impact resistance.

## 3 Overview of actuators

**(1) Development concept**

We decided to develop actuators intended mainly for use in the legs as shown in **Fig. 1** where both high speed and high thrust are required. For electric actuators, there is a risk of damaging the gear reduction mechanism due to unexpected impact during work, but for hydraulic actuators, which have higher impact resistance, it is possible to provide humanoid robots with a function to avoid damage by using oil compressibility and a highly responsive pressure relief mechanism.

**(2) Equipment configuration and specifications**

**Figure 2** shows the equipment configuration and hydraulic circuit of the electro-hydraulic actuator. **Table 1** shows the specifications of the electro-hydraulic actuator. The servo motor, hydraulic pump, valve unit, and hydraulic cylinder have been integrated into one unit, thereby forming a compact construction without piping between hydraulic devices. In addition, a closed-circuit configuration has been adopted that feeds oil to the cylinder according to

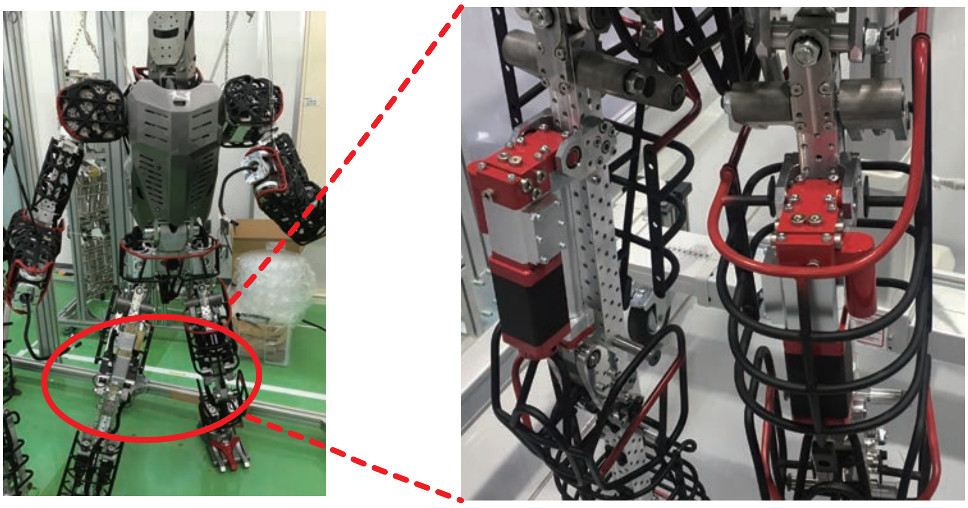
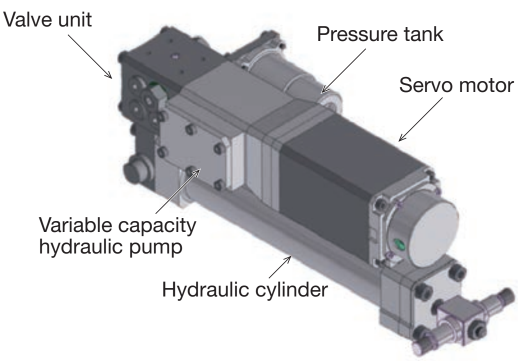
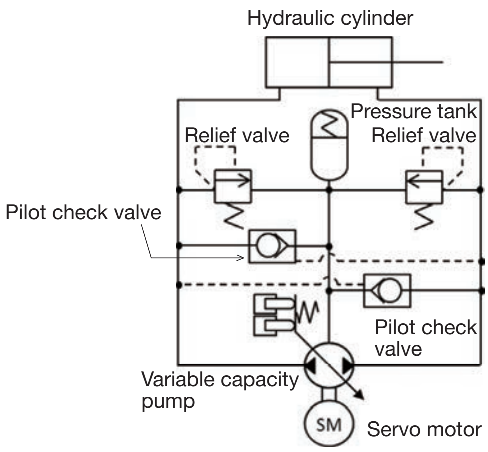


Fig. 1 Applying this technology to the legs of humanoid robot Kaleido




(a) Equipment configuration




(b) Hydraulic circuit

Fig. 2 Configuration of electro-hydraulic actuator

Table 1 Specifications of electro-hydraulic actuator

| | |
|---|---|
| Maximum thrust 〔N〕 | 6, 000 |
| Maximum speed 〔mm/s〕 | 200 |
| Head diameter 〔mm〕 | 22 |
| Rod diameter 〔mm〕 | 8 |
| Stroke 〔mm〕 | 156 |
| Impact resistance function | Yes |

the servo motor speed.

This actuator, like other electric actuators, can be driven by using a robot controller. By detecting the leg joint angle with a separate encoder, the servo motor is controlled to position the cylinder so that the desired angle can be achieved.

## 4 Details of development

In order to achieve size and weight reduction of the actuator, a good balance between high-speed, low-thrust motion and low-speed, high-thrust motion, and high reliability as well as high impact resistance, we developed the following technologies and methods.

**(1) Size and weight reduction**

(i) Developing a compact valve unit

To minimize the valve unit size, we set the number of valves to the minimum value required to realize the required functions and developed a new manifold containing specially designed valves and oil passages. The following parts need to be developed for the valves that make up the valve unit shown in **Fig. 3**.

① Relief valve

To release excessive external force that the actuator has received immediately and accurately by oil pressure, there is a need to achieve high responsiveness and reduce override characteristics, which cause the relief pressure to increase as the flow rate increases.

② Pilot check valve

When the actuator retracts, the valve is opened with low pump discharge pressure to return extra oil from the head caused by the difference in cylinder area to the pressure tank. In addition, the pressure loss is minimized to allow oil from the tank to flow smoothly into the actuator when the actuator advances.

To achieve the above functions and performance, we developed a compact cartridge valve. We reduced the number of oil passages in the manifold to a minimum and arranged the valves so that the minimum required thickness could be achieved around the oil passages, thereby achieving a manifold size of less than 40 mm square, which is the same as the servo motor size. In addition, we designed the internal diameter, length, and crossing shape of oil passages so that the smallest pressure loss could be achieved.

(ii) Integrating the valve unit, unit cover, and tank into one unit

Common hydraulic actuators consist of valves, cylinders, a pump, a tank, and other blocks connected to one another. Integrating these blocks into one unit eliminates the need to seal between blocks and provides enhanced flexibility in the layout of oil passages, thereby achieving further size reduction.

Therefore, we integrated the valve unit, cylinder head cover, pump valve cover, and tank connection block into one unit as shown in **Fig. 4**, taking the following into account.

① Optimizing the oil passages connecting the parts

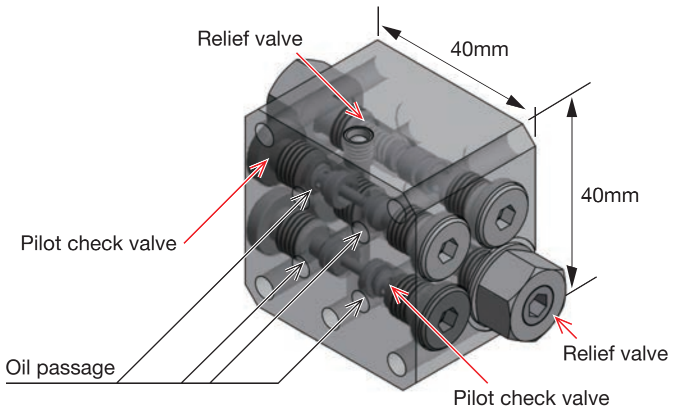



**Fig. 3 Valve unit**

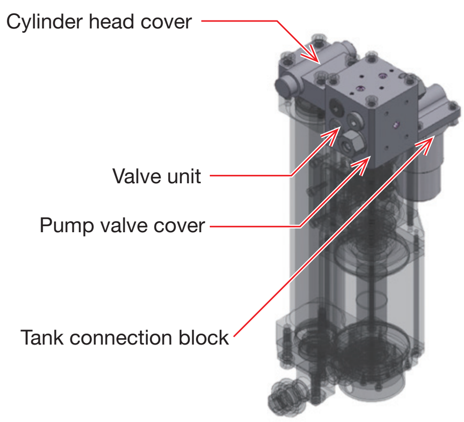



**Fig. 4 Integration of components**

The parts were connected linearly with the valve oil chamber, thereby achieving an efficient piping layout..

② Rethinking the tank volume

Tanks designed in conformity with general industrial machinery standards are too large. For application to robots, we set the tank volume to 1.1 times the minimum required volume rather than 4.2 times.

With these efforts, the distance between the actuator mounting position and pump mounting position was significantly reduced.

(iii) Integrating the hydraulic pump and servo motor into one unit

Initially, the hydraulic pump and the servo motor, which drives the hydraulic pump, were arranged coaxially with each other, and the shafts were spline-coupled. However, while using belts and gears reduces drive transmission loss, it leads to size increase and causes insufficient strength in the joints. To solve this problem, we integrated the drive shafts of the pump and motor into one unit as shown in **Fig. 5**. For this integration, we optimized the flange shape for connecting the pump and motor, oil seals, and bearings.

For the bearings used for the pump and motor, we used the same bearing in the middle between the pump and bearing, thereby reducing the number of parts and size. In addition, to prevent stress from being generated in the shaft, we adopted a slide bearing on the pump-side shaft end.

**(2) Achieving a good balance between high-speed, low-thrust motion and low-speed, high-thrust motion**

To achieve a good balance between high-speed, low-thrust motion and low-speed, high-thrust motion, which is required for humanoid robots, we needed a variable capacity hydraulic pump. Based on the swash plate piston pump technology we have accumulated in making construction machinery and industrial machinery, we developed a variable capacity swash plate piston pump with displacement from 0.75 $cm^3$ to 1.5 $cm^3$ as shown in **Fig. 6**.

This pump can supply high-pressure hydraulic oil to the actuator without causing an overload in the servo motor by optimally controlling the pump capacity according to the load pressure of the actuator. In addition, this pump has a mechanism to control the pump capacity in a stepless fashion according to the load pressure by optimally balancing the oil pressure generated on the piston and the spring load holding the slash plate angle. This mechanism not only efficiently converts the output from the servo

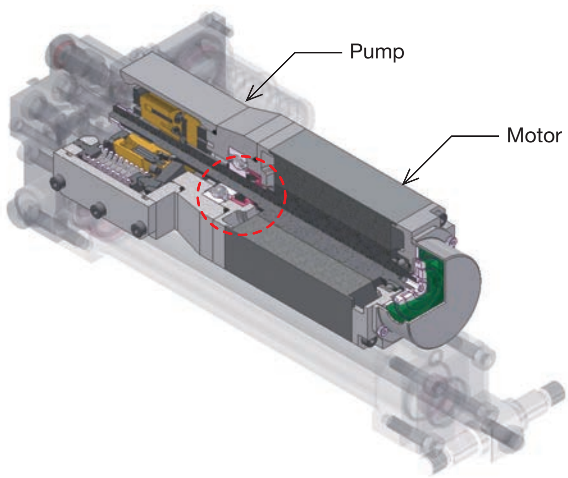



**Fig. 5  Integration of shaft**

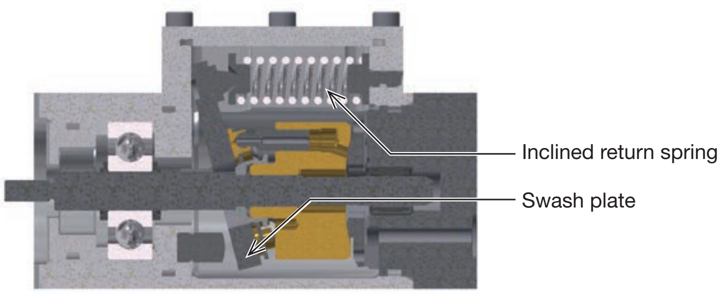



**Fig. 6  Swash plate type variable displacement axial piston pump**

motor to hydraulic energy, but also provides a simpler swash plate drive mechanism without a solenoid switching valve, thereby contributing to size and weight reduction.

The conventional system uses a solenoid switching valve to adjust the capacity in two steps; therefore, in order to allow the pump to operate continuously without causing an overload in the servo motor, there is a need to switch the capacity from high to low when the pressure rises, wasting some of the power. The pump we developed this time adjusts the capacity in a stepless fashion when the pressure rises and converts the power from the servo motor efficiently to hydraulic energy, thereby achieving high-speed, high-thrust motion in the entire pressure range with less power.

**(3) Improving reliability**

(i) Vibration damping control of the hydraulic cylinder

**Figure 7** shows a block diagram representing position control in the servo motor control system of this actuator. The actual position data is fed back with an encoder, and

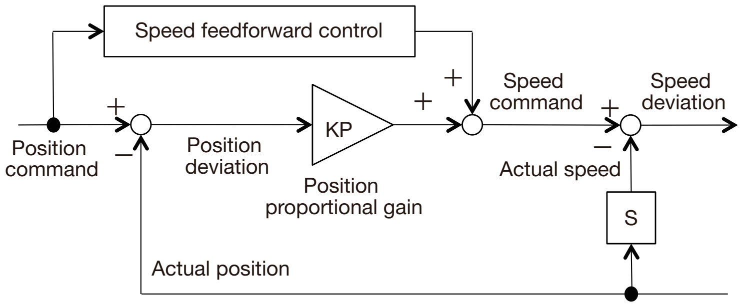



**Fig. 7 Block diagram of position control**

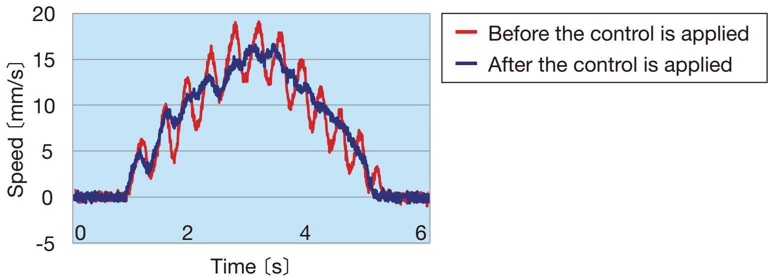



**Fig. 8 Effect of vibration suppression control**

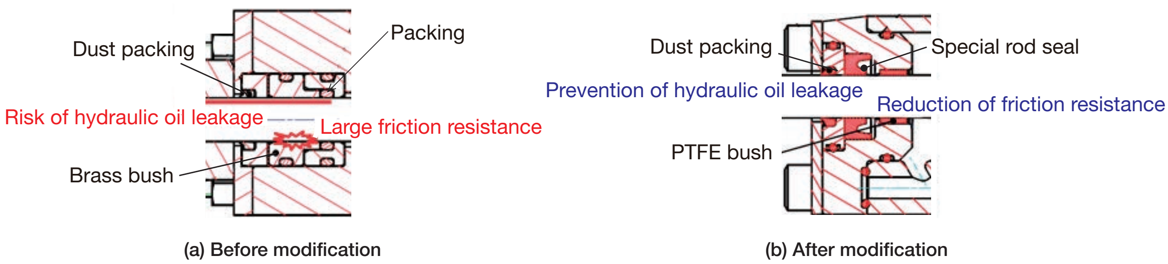



**Fig. 9 Modification of cylinder bearing rod**

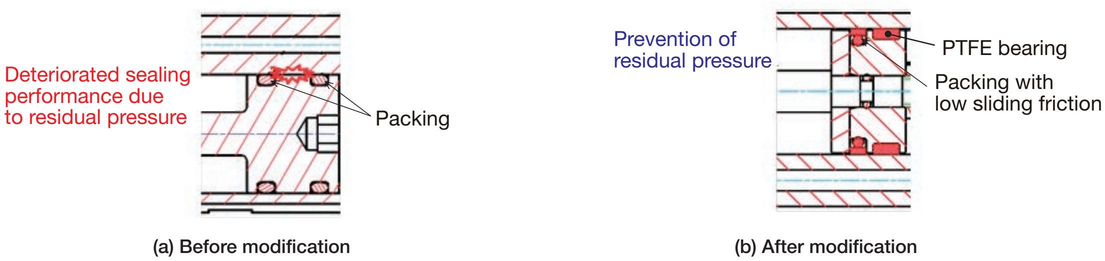



**Fig. 10 Modification of cylinder bearing piston**

speed commands are given to the motor based on the deviation between the actual position and position command. Because the position proportional gain is adjusted so that the responsiveness can be maintained even at high loads or speeds, the position proportional gain becomes too large at low loads or speeds, causing persistent vibration or hunting. This is attributable to a delay in the actuation of the hydraulic cylinder after the servo motor is activated and oil is discharged.

To prevent this, we developed a function to detect a low load or speed based on the motor current and motor speed and appropriately adjust the position proportional gain and gain in speed feedforward control. **Figure 8** shows the waveforms of the hydraulic cylinder speed at low load and speed before and after this control was applied. As shown in the figure, continuous vibration has been reduced significantly.

(ii) Modifying the cylinder bearing

We modified the cylinder bearing rod and piston. The rod initially consisted of a brass bush, seals, and dust packing, but with this configuration, there is a risk of hydraulic oil leaking if an external impact load is applied in the axial direction of the rod. In addition, the brass bush has a large frictional resistance. Therefore, we adopted a specially designed rod seal with enhanced pressure resistance as shown in **Fig. 9** and changed the bush material to PTFE, thereby eliminating the risk and problem.

The piston was initially structured so that it was supported and sealed by the piston seals. Depending on the operating conditions, however, there was a risk that hydraulic oil may intrude between two seals, resulting in deteriorated sealing performance due to residual pressure. To solve this problem, one PTFE bearing and one piston seal were arranged next to each other as shown in **Fig. 10**.

## Conclusion

Mounting electro-hydraulic actuators on humanoid robots is the challenge we are facing to achieve synergy between the hydraulic technologies and robot technologies Kawasaki has. Not only can this actuator be used for robots, but for autonomous mobile systems, production lines, and industrial machinery. As public relations efforts, we exhibited this actuator at IFPEX2017 and IREX2017 as a reference exhibit and registered its trademark as Hydro Servo Muscle.

Some people say that hydraulic technology is already mature. However, we will be pursuing size and weight reduction and user-friendliness to realize a system where both hydraulic technology and electric technology can be used, thereby creating something new.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# Evaluation Technologies That Support Boosting the Performance and Reliability of Hydraulic Components


*Improving evaluation technologies which support research and development is vital to continuing to develop hydraulic components that satisfy the advanced requirements of the construction machinery industry. Kawasaki is boosting the unit performance and reliability of hydraulic components through elucidation of their operation mechanisms, and at the same time, developing evaluation technologies for boosting the overall performance of hydraulic systems that combine multiple hydraulic components and utilizing these technologies for product development.*

## Introduction

Because of increasingly tighter diesel engine emissions regulations and $CO_2$ emissions regulations around the world, there are increasing needs for fuel consumption reduction in the field of construction machinery, including excavators. In addition, there is a growing shortage of experienced operators at construction sites, so easier excavator operation is required. Moreover, efforts toward improving the efficiency and quality of the entire construction process are becoming active, and construction machinery manufacturers and construction companies are playing a central role in researching and developing automation and computer-aided construction technologies.

## 1 Background

In response to the needs for fuel consumption reduction in the excavator industry, we have been working to improve the efficiency of individual components. Our hydraulic pumps have achieved the highest maximum efficiency in the world at over 90%, but we are continuing research and development to further improve the efficiency. We are also working to improve the reliability of hydraulic components to meet the needs of construction machinery manufacturers, as reliability is important as well as performance.

In recent years, boosting not only the unit performance of hydraulic components but also the overall performance of the entire hydraulic system combining hydraulic components, including fuel consumption, work efficiency, and operability, are drawing attention. We are dedicated to developing hydraulic components taking into account how individual hydraulic components affect one another when they are operated as a system.

## 2 Concept of evaluation methods

To achieve this kind of product development, we are required to more accurately grasp phenomena and verify hypotheses, which is to say, improve our evaluation technologies. Kawasaki began the operation of HYPAM in 2005, which is a hydraulic component evaluation bench that can measure and evaluate the performance of individual hydraulic components and operating mechanisms of hydraulic components, and has been using HYPAM for product development while improving evaluation technologies. In addition, in order to evaluate hydraulic components for excavators as a system, we developed a new hydraulic system evaluation bench, HILS (Hardware-In-the-Loop Simulator), and began its operation in 2018.

## 3 Hydraulic component evaluation bench HYPAM

**(1) Features**

We began the operation of the hydraulic component evaluation bench HYPAM (**Fig. 1**) in 2005 for hydraulic

Fig. 1  Evaluation bench for hydraulic components HYPAM

pumps only, but have been using it for hydraulic motor evaluation since 2006, and for excavator control valve evaluation since 2018.

For hydraulic pumps, we have improved measurement and testing methods, including using high-accuracy sensors and developing dedicated measurement software, to grasp slight efficiency differences, thereby contributing to efficiency improvement. In addition, we have been installing various sensors inside pumps to grasp the behavior of each internal component and using obtained knowledge to improve optimal design technologies with the aim of realizing high-performance hydraulic components. In recent years, to meet increasingly stricter requirements, including further size reduction, maximum speed increase, controllability improvement, and service life extension, we have been focusing on elucidating the dynamic and transient phenomena occurring inside hydraulic components by combining HYPAM with simulation technologies. With the know-how on simulation we have accumulated in developing various products, including energy-related products and transportation-related products, we are continuously improving HYPAM so as to more accurately predict actual phenomena by enhancing simulation model accuracy and tuning simulation parameters based on the results of measurement with HYPAM.

**(2) Application examples**

The following introduces a recent application example of the hydraulic component evaluation bench HYPAM for cavitation in pumps.

When the hydraulic oil pressure in a hydraulic pump drops rapidly, cavitation may occur, which is a phenomenon in which dissolved air forms air bubbles. When the pressure rises, these air bubbles collapse, sending a strong shock to the surroundings, causing damage to the machine surface. That is why cavitation also causes damage to fluid machinery, such as ship screws and rocket pumps. For piston pumps, the valve plate, cylinder bore inner surface, and other parts that are exposed to cyclic pressure fluctuations may be damaged in various forms as shown in **Fig. 2** due to cavitation caused mainly by rapid switching operation, so taking measures is extremely important.

Therefore, we evaluated cavitation risks by means of large-scale 3D unsteady fluid simulation and studied measures in the design stage. Ensuring simulation accuracy of appearance and disappearance of air bubbles with this fluid simulation requires tuning physical parameters in the two-phase model used in the simulation, and the pressure fluctuation measurement data in each section of the pump we have accumulated over the years with HYPAM can be used for the simulation. This facility

Fig. 2  Example of cavitation erosion on valve plate

incorporates the technology to control operating conditions in sophisticated ways and the technology to accurately measure pressure, temperature, input torque, and other parameters. These technologies are working effectively.

Also, we are working to directly observe air bubbles locally generated by cavitation. With a laser pulse light source and a high-speed camera, air bubbles inside the cylinder bore are observed from the pressure-proof window as shown in **Fig. 3**. This observation allowed us to grasp the relation between the operating conditions and air bubble distribution and confirmed high reproducibility even for local flow in the fluid simulation (**Fig. 4**), encouraging us to actively use simulations in product development.

This approach is an application example of HYPAM for improving pump performance, but the same approach has been applied to other hydraulic components, such as hydraulic motors and control valves, contributing to enhancing Kawasaki's ability to develop hydraulic components.

Recently, we are focusing on evaluating the dynamic characteristics of individual hydraulic components, especially the spool switching operation of the control valve, which affects the operability and responsiveness of the entire hydraulic system, and collecting data with the aim of enhancing product performance and reliability using the collected data along with the results of evaluation by HILS, which will be described later.

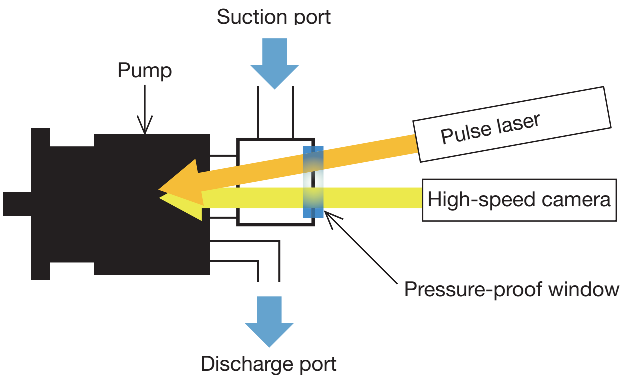



**Fig. 3 System for observing cavitation bubbles in hydraulic pumps**

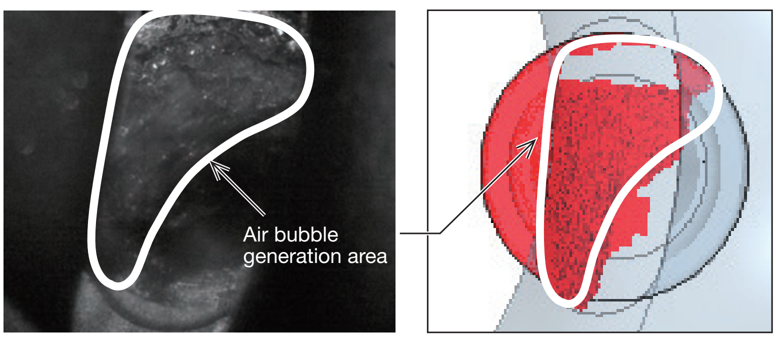
## 4 Hydraulic system evaluation bench HILS

### (1) Features

Comprehensively boosting the performance of the entire hydraulic system requires taking account of interactions among the hydraulic components making up the system, but it is difficult to do so with HYPAM only, which evaluates hydraulic components alone. Hydraulic component systems had been evaluated only by conducting tests with actual machines. However, actual machines do not have sufficient space around the hydraulic components, so measurement conditions are restricted. In addition, the testing environment is unstable because it changes depending mainly on weather and soil conditions. Therefore, we developed HILS, the hydraulic system evaluation bench shown in **Fig. 5** with the aim of achieving system evaluation by testing hydraulic components on bench.

HILS is a simulator that combines actual and virtual things to evaluate systems. HILS allows a virtual excavator to operate in conjunction with a hydraulic system consisting of hydraulic components, such as pumps and motors, and gives appropriate loads to the hydraulic system according to the operation.

As shown in **Fig. 6**, the hydraulic system evaluation bench HILS is composed of actual hydraulic components, a virtual excavator, and load equipment. The actual hydraulic components include the main pump, control valve, pilot valve, and controller making up the system. The virtual excavator is a simulation model that simulates the excavator boom, arm, bucket, swinging and other actuator mechanisms, and dynamics, including loads, such as sand, in the HILS computer. Hydraulic loads, including the pressure and flow rate between the hydraulic cylinder and




(a) Observation result　　(b) Simulation result

**Fig. 4 Observation results of cavitation bubbles in cylinder and comparison with simulation results**

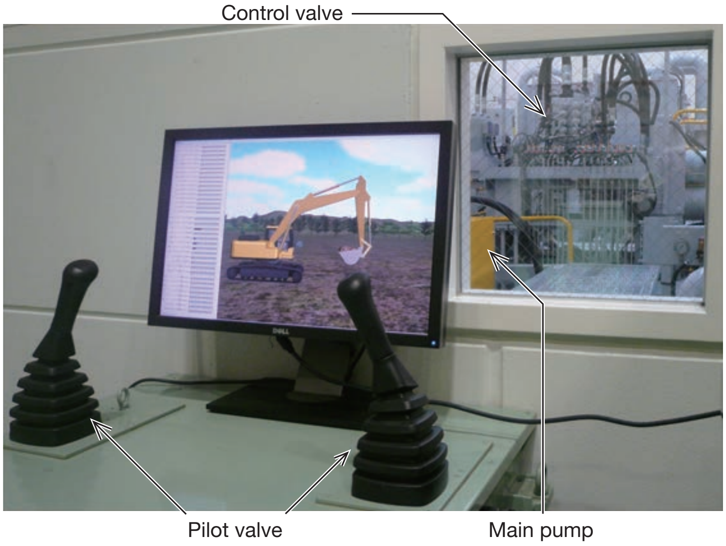



**Fig. 5  Evaluation bench for hydraulic systems HILS**

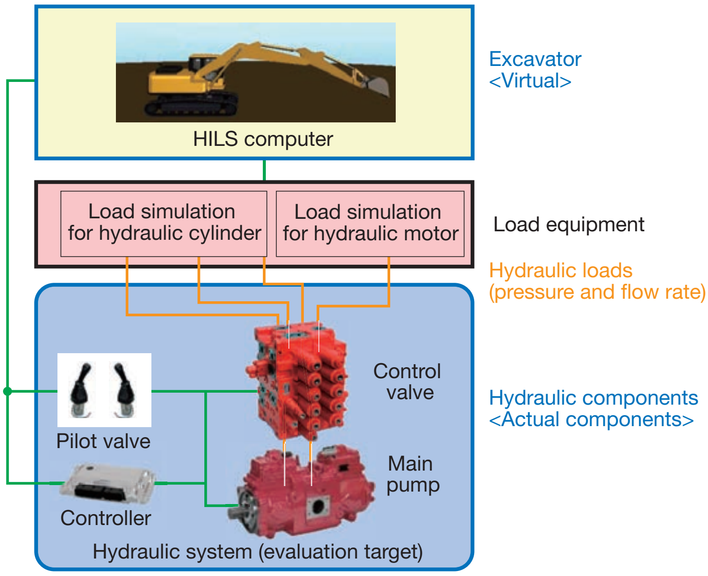



**Fig. 6  Configuration of HILS**

hydraulic motor, which serve as an actuator for the excavator, and the control valve, are controlled by the load equipment. Based on the load generated by the oil fed from the hydraulic pump to the actuator via the control valve, HILS simulates the behavior of the excavator from moment to moment and at the same time controls the hydraulic load with the hydraulic equipment to simulate dynamic behavior of the excavator. HILS can be used to simulate the speed, displacement, pressure, flow rate, and other state quantities of the excavator hydraulic cylinder and hydraulic motor necessary to evaluate the hydraulic system. HILS can also be used to evaluate and analyze the operation of each hydraulic component and fuel consumption of the entire system by installing pressure sensors, flow rate sensors, and other sensors onto the main pump and control valve ports. In actual excavators, the main pump is driven by an engine but on this bench, the main pump is driven by an electric motor that is controlled to simulate the engine characteristics.

**Figure 7** shows the waveform of boom-up operation as an example of HILS operation. HILS simulates fluctuations in the pump pressure, cylinder head pressure, and cylinder rod pressure, and the cylinder displacement in simulations that takes place on an actual excavator when the hydraulic oil discharged from the pump is fed to the boom cylinder via the control valve.

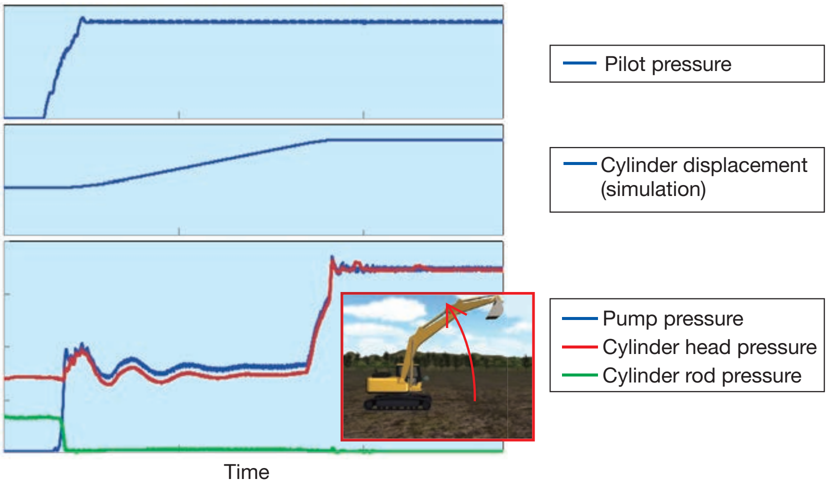



Fig. 7  Example of HILS operation (response to boom-up operation)

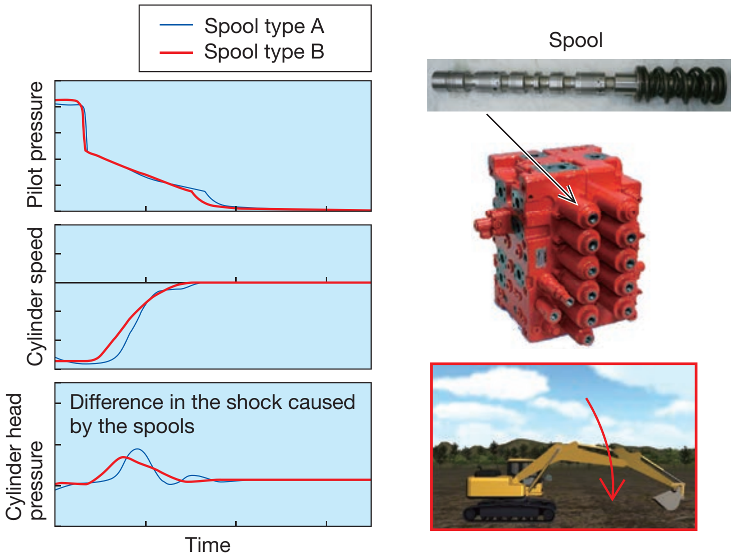



Fig. 8  Evaluation of operability with HILS (shock behavior when the boom stops moving down)

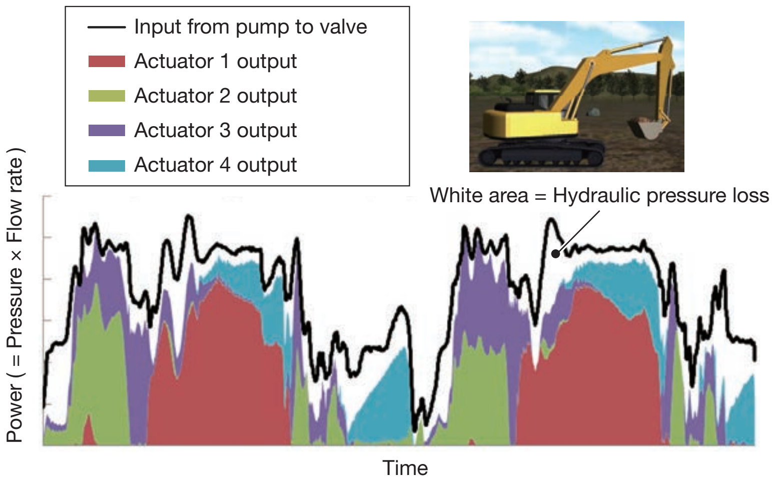



Fig. 9  Evaluation of efficiency with HILS
(Power balance of control valve at digging and loading operation)

**(2) Application examples**

(i) Excavator operability evaluation

When boom-down operation is stopped by operating the operation lever, a large shock may occur depending on the characteristics of the control valve and pump, resulting in complaints from the operators. **Figure 8** shows an example of evaluation of the shock caused when boom-down operation is stopped. This example is the evaluation conducted when the spool specification (notch shape) of the control valve was modified. In this simulation, it was difficult to accurately simulate the dynamic behavior of the spool mainly because of a flow force generated when hydraulic oil passes through the notch, so it was necessary to test the spool by mounting it in an actual excavator. However, we found that the evaluation results obtained with HILS were almost the same as those with the actual excavator.

(ii) Fuel consumption evaluation

**Figure 9** shows an example of evaluation of control valve efficiency (hydraulic energy loss) in soil excavation and loading operation. This figure shows the power input from the pump to the control valve and power output to each actuator. The difference between them is hydraulic pressure losses. Hydraulic components can be improved by analyzing which section has the most power loss. In addition, torque sensors and pressure sensors are installed on the drive shaft of the main pump, thereby making it possible to measure the total efficiency.

As mentioned above, HILS has made it possible to perform internal evaluations equivalent to a test with the hydraulic component mounted on the actual excavator before conducting such a test. Using this evaluation to analyze the performance required for system operation, we are developing hydraulic components by combining this evaluation with the performance test using the above-mentioned HYPAM. In this way, the combination of HYPAM and HILS has made it possible to develop hydraulic components that pursue, not only the performance and reliability of hydraulic components alone, but also the comprehensive performance of the entire hydraulic system in a significantly reduced amount of time.

## Conclusion

We will be working to realize more reliable hydraulic components with the combination of HYPAM and HILS. We will also be working to improve the technology to measure hydraulic components at high speed and the technology to simulate the transient operating condition for grasping the details of dynamic phenomena and at the same time improve the accuracy of actual excavator simulation, with the aim of developing objective evaluation indicators for fuel consumption, work efficiency, and operability and enhancing our ability to develop hydraulic components.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# ICT and IoT Technology for Further Global Expansion of Production

*Kawasaki is promoting the global production of hydraulic equipment and has established a system for boosting manufacturing capabilities with Nishi-Kobe Works and has continued to be a top brand in the field of hydraulic equipment.*

*In recent years, with the aim of catching up with rapidly changing global customer requirements, Kawasaki has been promoting the visualization of cost and production capabilities and working to realize a production system for local production and consumption through utilizing ICT (Information and Communication Technology) and IoT (Internet of Things) technology.*

## Introduction

In the construction and agricultural machinery markets, construction and agricultural machinery manufacturers are expanding their production and sales globally to address expanding markets in emerging countries and reduce exchange risk. They are keeping up with this a shift in the market through local production and consumption[1].

## 1 Background

Because construction and agricultural machinery manufacturers, which are Kawasaki's customers, are expanding their production and sales globally, there is an urgent need for Kawasaki to have a production system that enables local production and consumption in producing hydraulic equipment.

Regarding Nishi-Kobe Works as the mother factory for overseas production bases, Kawasaki has been producing rotary parts only in Japan, thereby remaining competitive in terms of quality and delivery. Rotary parts are used in hydraulic motors and pumps, which require core technologies and are called core parts.

To meet increasingly diverse customer needs and increasing demand, Kawasaki is required to further promote globalization, which means producing finished parts and core parts at overseas production bases with the same level of management.

## 2 Challenges faced in the core parts strategy and global expansion of production

Under the core parts strategy[2], Kawasaki has been supplying core parts from Nishi-Kobe Works to overseas production bases for differentiation in cost and quality. In addition, Kawasaki has been working to thoroughly eliminate overburden and waste and ensure full use of equipment and manpower by promoting KPS (Kawasaki Production System) in its production sites with the aim of reducing cost and enhancing quality.

However, as the number of production models increase to meet diversifying customer needs, a substantial number of man-hours are needed to modify standard operations for operators. The required production model may change when standard operations have been modified. In addition, because of the increasing demand, it is becoming difficult to meet the customer-required lead time by supplying core parts from Nishi-Kobe Works only. Moreover, Kawasaki has so far remained competitive in quality and price by focusing on managing core parts but will be required to enhance the management level of other parts to strengthen its competitiveness.

To address these challenges, we decided to further expand our production globally. However, we will not start producing core parts at overseas production bases if the conditions are not met, due to the risk of quality degradation or technology leakage even it would reduce the cost or lead time. Taking this into account, we decided to look into the following two specific measures.

① Changing production models flexibly to meet diversifying customer needs and ensuring prompt response to such changes for efficient production.
② Having overseas production bases produce core parts that require relatively easy production and quality management.

## 3 Importance of ICT and IoT technology in global expansion of production

Changing production models flexibly and producing some core parts at factories other than Nishi-Kobe Works is essential to keep up with customers' globalization. In addition, maintaining superiority in quality is necessary to maintain a high market share and avoid involvement in product price competition.

In further expanding production globally, ICT and IoT technology contribute to achieving the same level of quality and productivity at lower cost and making adequate use of production know-how from the startup of the production line as well as these technologies makes it possible to offer customers the same value from different production bases.

## 4 ICT and IoT technology for global expansion of production

To expand production globally, we put emphasis on visualization in each production phase using ICT and IoT technology.

### (1) Visualization of production plans and results in machining processes

Every production base has machining processes for various parts, and Nishi-Kobe Works has the largest scale of machining processes. Amid the increasing demand, maintaining the equipment operating rate at the maximum level is important to satisfy the customer-required lead time.

In making investments in machining equipment, each production base is required to have a system for efficient use of equipment. Therefore, we visualized the operating condition of machining equipment so that both the supervisor and operator can keep track of the progress of production and also the supervisor can give efficient work instructions.

First, we developed a system for giving efficient work instructions to an FMS (Flexible Manufacturing System), which is shown in **Fig. 1** and has been adopted in several places in Nishi-Kobe Works and keeping track of work results.

An FMS can machine multiple models at the same time. Available machining equipment depends on the model, so if the number of models machined at the same time is large, the output changes depending on the work sequence. In addition, FMSs should be operated in conjunction with the assembly line, so the operators need to perform their work while accounting for the following:
① Accomplishing the instructions given on the production management board.
② Recording work results.
③ Minimizing the operation loss of the equipment each operator is in charge of.

Supervisors may create a plan to make full use of equipment but the achievement rate changes depending on the proficiency level of each operator. Many man-hours are needed to efficiently analyze the difference between the plan and the achievement rate.

Therefore, we introduced a work instruction system to

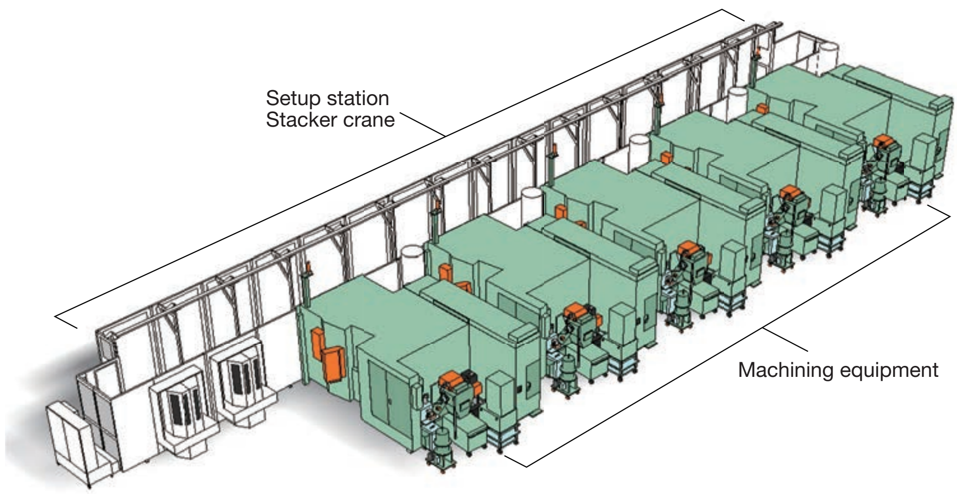



**Fig. 1 Overview of FMS (Flexible Manufacturing System)**

automatically create the operator's work sequence and equipment operation plan based on the production plan as shown in **Fig. 2** so that anyone can plan and execute the same work sequence.

With this system, the equipment operating rate in hydraulic pump part machining lines has improved by an average of 5 to 10%. In addition, it has become possible to visualize problems even if the equipment operating rate does not improve.

At overseas production bases, in general, one operator is in charge of multiple pieces of equipment. Currently, this system gives work instructions to FMSs but it can also give work instructions to operators with the same concept.

This enables production bases that introduce the system into their lines to perform the same level of improvement activities as the Nishi-Kobe Factory without depending on the supervisor's ability.

**(2) Visualization of work in assembly processes**

At Nishi-Kobe Works, hydraulic equipment of different types is produced in an assembly line for cost reduction.

In mixed production lines, new operators and experienced operators work together on the same line, so the bottleneck process changes constantly depending on the operator and product. In these lines, the supervisors have difficulty immediately identifying where a problem has occurred and taking necessary actions to remedy it.

To solve this problem, we developed a system that can automatically obtain detailed data on each production process and analyze the progress of production in real time, i.e., visualized work.

**Figure 3** shows the process information obtained by this system. This system collects work data in each process from the sensors installed on a production line and displays the obtained data with the BI (Business Intelligence) tool. This has enabled early problem detection with the visualization of line status. In addition, variations in standard time can be minimized by optimizing the sequence of loading products onto the assembly line.

Differences between the assembly plan and result, which are currently analyzed based on the supervisor's ability, depend mainly on the product loading sequence, production model, and operator, so cannot easily be analyzed. The newly developed system is able to quantify the differences by visualizing work and in addition, can evaluate the effectiveness of improvements in the same manner. This system makes it possible to quantify problems in production lines, thereby eliminating management dependent on individuals.

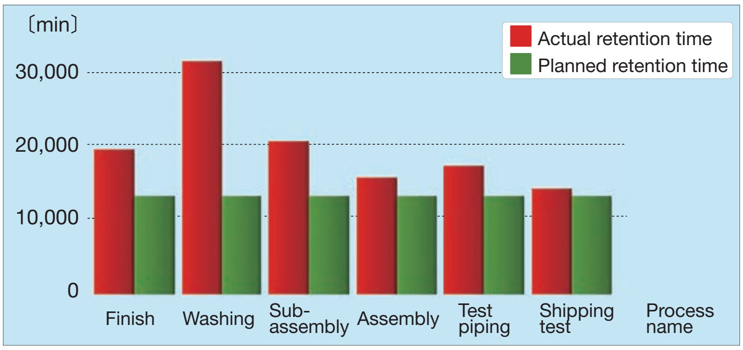
Introducing this system into each production base provides standardized production line management procedures, thereby making it possible to detect problems early regardless of the production volume. This system also provides efficient line improvement with a unified way of thinking in response to requests for cost reduction and lead time reduction.

**(3) Visualization of cost**

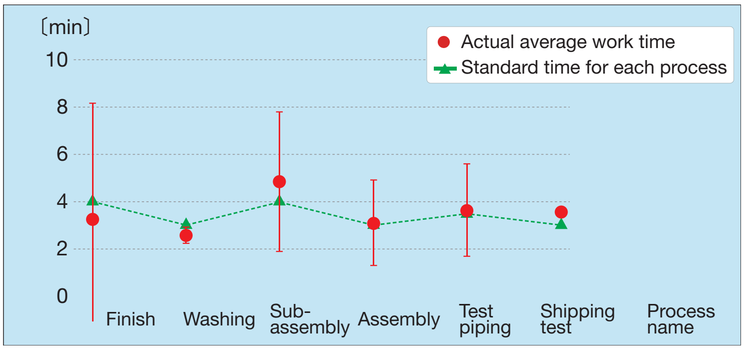
The cost management system currently used in Nishi-Kobe Works is based on the system introduced in 1986 and its operation began in 2006.

After mechanization and automation in 2011, it became


Fig. 2 Overview of operation instruction system




(a) Total retention time in each process




(b) Average work time for each process and variation

Fig. 3 Collected process information

difficult to evaluate cost in a uniform manner due to uneven automation. In addition, labor saving is required for cost calculation and it is better for the actual production volume to be grasped automatically.

These problems are expected to arise at other production bases in globally expanding production, and measures are needed. To solve these problems, we decided to introduce a new cost calculation method and quantify and visualize cost, which changes according to the circumstances, so as to address globally expanded production.

**Figure 4** shows the overview of the new cost calculation method. The machine rate, which represents the equipment operating cost per hour, is calculated based on the equipment operation time obtained from machining equipment. If the operator's work time, including assembly and operation, is the dominating factor, then the man rate, which represents the operator's labor cost per hour for each of the processes, is set based on the work time automatically measured by the sensors installed in the production line. By combining those rates, we aimed to obtain more detailed cost information.

Major improvements brought about by the new cost calculation method are as follows:

① The target cost reduction can be clarified by visualizing the details of cost for each product model.

② In rate calculation, the operation time for each piece of equipment is measured and calculated automatically, enabling significant labor saving.

The new cost calculation method enables not only accurate cost control but also strong linkage between management and production line improvement, thereby making it possible to clarify what to focus on for cost reduction. In addition, with this method, it is possible to identify departments responsible for each factor through detailed cost analysis, enabling strong promotion of improvement activities.

Introducing this new cost calculation method into each production base will enable global cost evaluation. Cost is a customer need that customers put particular emphasis on. This method enables accurate decision making through cost comparison for each production base. We think that this will make it possible to formulate appropriate business strategies for the management plan.

**(4) Visualization of supply chain**

In expanding production globally, global procurement is an important issue as well. With the conventional management method, if a product is purchased nearby, the delivery can be confirmed adequately through close communication, so problems are unlikely to occur. In global procurement, however, suppliers exist worldwide, so

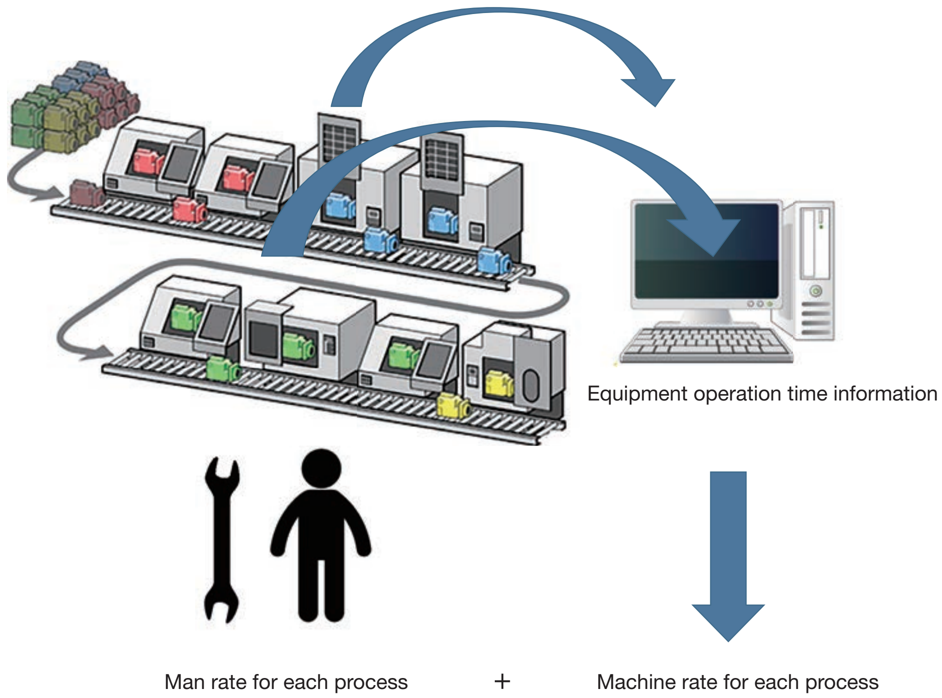



**Fig. 4 Overview of new cost calculation method**

several additional items must be considered.

Taking hydraulic pumps as an example, even they consist of over 40 kinds of parts (which is a relatively small number) so even if production activities are managed properly within the factory, a delay in the delivery of even one part will result in a failure to meet the delivery date required by the customer. Globalized procurement requires complicated delivery management for purchased products.

To address this problem, we decided to visualize the supply chain. More specifically, the production management workflow used in Nishi-Kobe Works, as mother factory, is used as a model so that it can be used by suppliers as part of the production management system. This makes it possible to share the basic concept of production management with suppliers.

**Figure 5** shows an overview of the modeled production management procedure. The current operation workflow consists mainly of equipment capacity estimation,

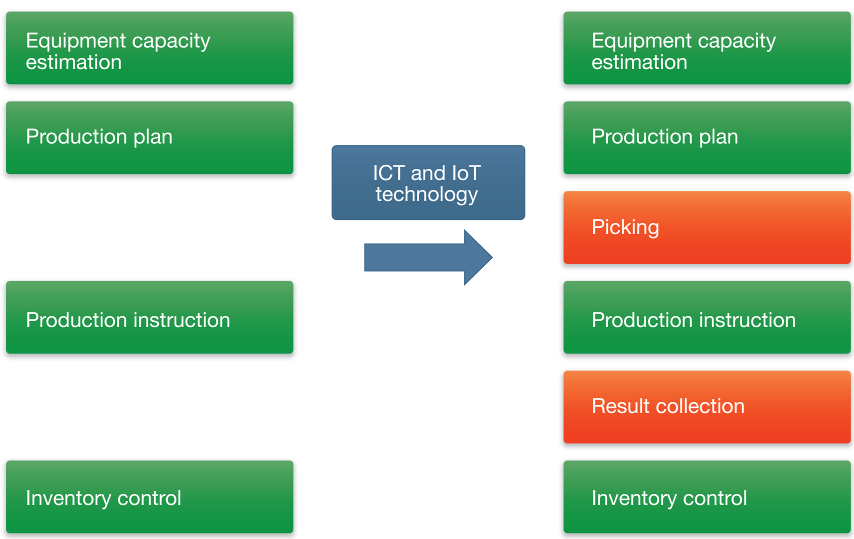



**Fig. 5 Modeled production control method**

production planning, production instruction, and inventory management. A new production management system will be established by adding picking and result collection using ICT/IoT technology to the workflow.

This production management system enables borderless delivery and inventory management even under a globalized production system.

## Conclusion

In order to meet global customer needs, we established a foothold for expanding our production globally with the same management level as Nishi-Kobe Works through promotion of visualization using ICT and IoT technology. This has allowed us to promote a production system for local production and consumption.

We will be working to establish a flexible production system that can respond to varying customer needs and promoting technical innovation as a top brand in the field of motion control.

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# K7V-Series – Swash Plate Type Axial Piston Pump


*Out of consideration for the global environment, interest in saving energy and enhancing performance is increasing in the excavator market, and that is why we developed the K7V series of next-generation pumps to meet those demands. Hydraulic systems are required to have higher total efficiency and higher operation speed. To offer products with these features, we applied the latest efficiency enhancement technology and assumed a high input torque in designing the K7V series, thereby achieving the highest level of efficiency and output density in this class as well as high reliability.*

## Introduction

China, India, and other countries have developed rapidly, causing the globalization of the construction machinery market to expand rapidly as well. At the same time, there is growing awareness about the global environment in the construction machinery as in other markets. Recently, efforts for energy saving are as essential in the construction machinery market as they are in the automobile market.

## 1 Background

Recently, the market environment and trends in the construction machinery field are changing drastically. For example, environmental regulations are becoming tighter and tighter, energy saving is becoming more and more important, and hybrid systems and electronic controls are becoming more prevalent. Construction machinery manufacturers are developing models that can respond to these changes, and hydraulic equipment such as pumps is required to have higher performance and reliability.

Over 30 years have passed since the K3V series and K5V series, which are bestselling pumps for excavators, were developed and put on the market. These series have high reliability and versatility, and have been used in various kinds of construction machinery, including excavators. In recent years, with an increasing interest in environmental preservation and energy saving, hydraulic pumps are required to have functions and performance that match the increasingly diverse market trends and customer orientation, such as being more efficient and compact. To respond to these requests, we developed the K7V series, which replaces the K3V series and K5V series.

## 2 Specifications

The K7V series was developed with the goal of overwhelming the performance of the previous series and competitors' products in every way. The rotary parts, which are the core parts of pumps, were totally redesigned to achieve higher efficiency and reliability than the previous series. **Figure 1** shows a sectional view of the K7V series pump with the major rotary parts, and **Table 1** shows the lineup and specifications of the K7V series.

### (1) Pressure specifications

The K7V series has the same rated pressure as the previous series at 35 MPa, which is common for excavators, and the K7V series' rotary parts were designed so that K7V pumps could be used for construction machinery other than excavators and handle future increases in pressure. The K8V series, which is a pump for closed circuits that uses the same rotary parts, has a rated pressure of 42 MPa.

### (2) Displacement

As an energy saving effort for diesel engines, which are the main source of power for excavators, construction



† The K7V Series, a high-efficiency, low-noise, compact, and high-reliability hydraulic pump, has been widely used for construction machinery (mainly excavators).

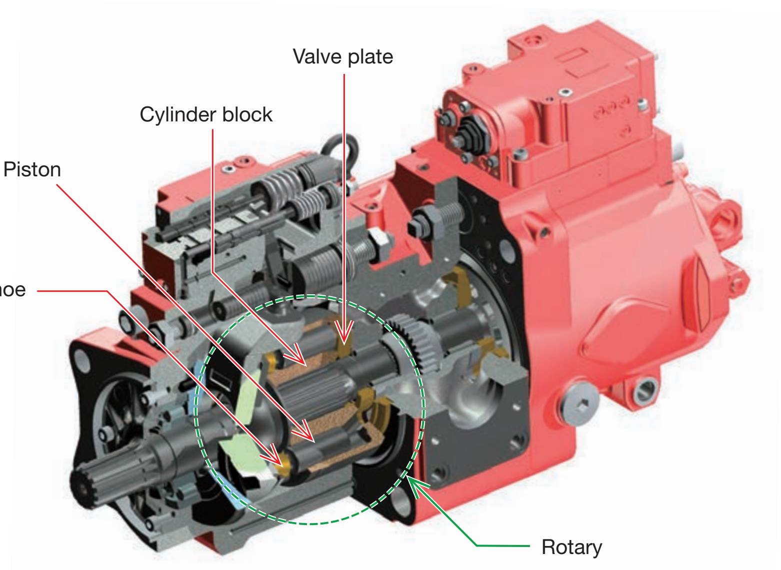

Fig. 1 Cross sectional view and major rotary parts of K7V series

Table 1 Specifications of K7V series

| Size | 125 | 140 | 160 | 180 | 280 |
|---|---|---|---|---|---|
| Maximum displacement 〔$cm^3$〕 | 130 | 140 | 160 | 180 | 280 |
| Rated pressure 〔MPa〕 | 35 | 35 | 35 | 35 | 37 |
| Peak pressure 〔MPa〕 | 40 | 40 | 40 | 40 | 42 |
| Maximum self-priming speed 〔$min^{-1}$〕 | 2, 360 | 2, 200 | 2, 100 | 2, 000 | 1, 800 |
| Maximum speed 〔$min^{-1}$〕 | 2, 700 | 2, 500 | 2, 350 | 2, 300 | 2, 100 |
| Maximum input torque 〔N·m〕 | 931 | 931 | 1, 500 | 1, 500 | 2, 500 |

machinery manufacturers tend to decrease the engine speed. To maintain the excavator operation speed with a reduced engine speed, higher pump displacement is required. To meet the trend and needs in the market, the displacement was set so that a sufficient discharge flow rate could be achieved.

## 3 Features

**(1) High efficiency**

The fuel economy of construction machinery is directly affected by the pump efficiency, so customer requirements for pump efficiency are extremely high. The

K7V series' overall shape and major dimensions that determine the pump performance were optimized to achieve the world's highest level of efficiency. In order to optimize the major dimensions, we developed a program that enables accurate pump efficiency estimation by quantifying the loss generated in each section between rotary parts based on accurate efficiency measurement results to accurately grasp the influence of each design factor. With this program, major dimensions were determined as shown in **Fig. 2** by setting constraints such as interference and strength, and combining major dimensions so that the highest efficiency could be achieved with minimum loss under these constraints.

**Figure 3** shows the efficiency measurement results of the existing K3V112 and the new K7V125. With the maximized effect of optimization, the K7V series has achieved higher efficiency than existing pumps by 3 point percent or more in the normal operation range.

**(2) High power density**

To increase the pump displacement for reduced engine speeds, a higher permissible input torque than that of existing pumps was achieved by increasing the strength of internal parts.

Also, to reduce cavitation, the shapes of the flow paths in the sections with high pressure loss were optimized by visualizing the pressure loss in the paths by means of CFD analysis. As a result, the K7V series has achieved a higher maximum self-priming speed than existing pumps.

**(3) High reliability**

Because of the increasingly globalized market, excavators are being used in severe conditions more often, requiring pumps to have higher reliability. At the same

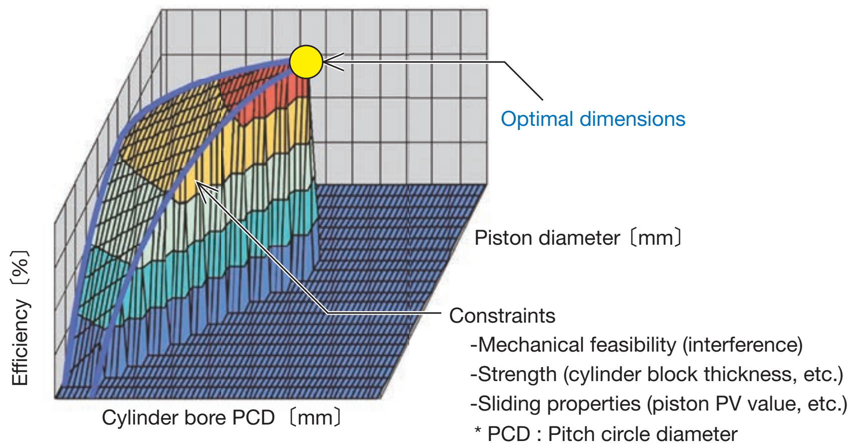


**Fig. 2 Optimization of cylinder bore PCD and piston diameter**

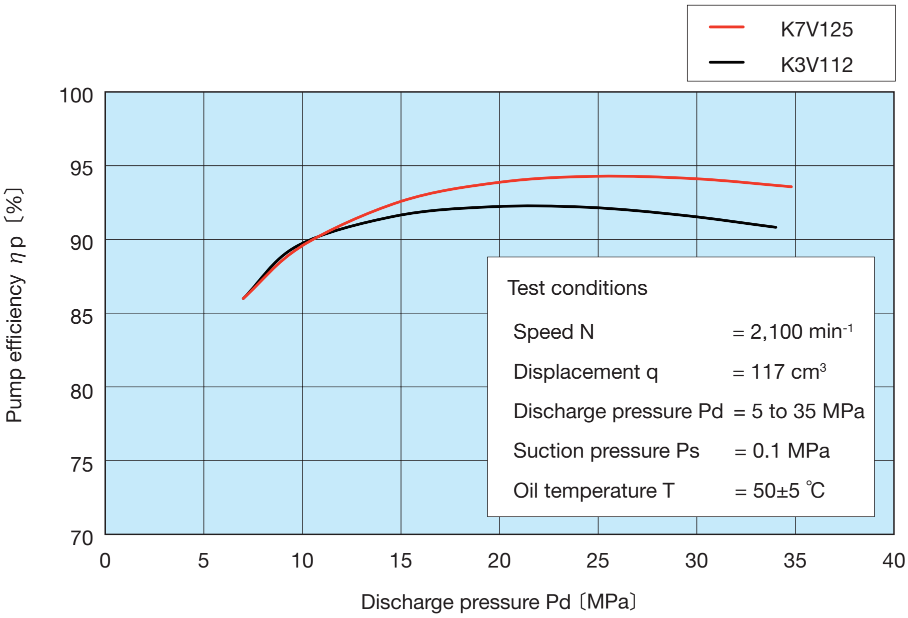


**Fig. 3 Pump efficiency measurement results of K7V125 and K3V112**

time, because of increased pressure and torque, the rotary parts are forced to slide under harsher conditions than before, requiring lower contact pressure on the sliding surface. For the K7V series, the local contact pressure was reduced by optimizing the shape of the sliding surface by means of elastic fluid lubrication analysis, thereby preventing seizure and enhancing reliability.

## Conclusion

Currently, the K7V series comes in five sizes, every of which enjoys a good reputation from customers. We will be continuously expanding the lineup to respond to market needs.

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# K8V-Series – Closed Loop Swash Plate Type Axial Piston Pump, and M7V-Series – Swash Plate Type Axial Piston Motor


*With the globally growing demand for infrastructure construction, the demand for construction machinery, including wheel loaders and cranes, is increasing. Kawasaki developed the K8V series, which is a pump for closed circuits adopted mainly for construction machinery, and the M7V series, a motor for actuators used mainly in winches. In addition, using a combination of the K8V series and M7V series enables optimal configuration of hydraulic continuously variable transmission systems (HST: Hydro-Static Transmission).*

*For the K8V series, we applied the technologies we have accumulated over the course of many years along with new technologies, including the efficiency simulation adopted for the latest flagship pump, thereby achieving high efficiency and low noise. For the M7V series, we used a swash plate motor, which is one of Kawasaki's strong suits, as the base and applied new design technologies, including an 11-piston configuration, thereby improving the maximum speed and stability at low speeds at the same time.*

## Introduction

Because of the remarkable economic growth in emerging countries, the demand for infrastructure construction is expanding globally. Accordingly, the demand for construction machinery essential for infrastructure construction, including wheel loaders and cranes, is increasing.

## 1 Background

Closed circuits, which are common in construction machinery, use only pumps and motors to circulate oil, which eliminates the need to install valves in circuits to change the oil flow direction. Therefore, unlike hydraulic pumps for open circuits, such as Kawasaki's K7V series and K3VLS series, hydraulic pumps for closed circuits need to have a mechanism to discharge oil in both directions. In addition, hydraulic motors that serve as actuators for cranes and other machines are required to be capable of rotating at higher speeds and rotating stably even at low speeds at the same time.

For entry into these fields, Kawasaki has developed the K8V series—swash plate axial piston pump suitable for use in closed circuits, and the M7V series—swash plate axial piston motor suitable mainly for crane winding. In addition, using a combination of the K8V series and M7V series enables optimal configuration of hydraulic continuously variable transmission systems (HST: Hydro-Static Transmission). HST is a transmission that discharges oil with a pump driven by an engine or other prime mover and allows the oil to rotate a motor to drive the wheels or the like (**Fig. 1**). HST can adjust the transmission ratio steplessly by adjusting the displacement, and change the direction of wheel rotation by changing the direction of the oil flow from the pump.



† The K8V Series, a dual-tilting hydraulic pump with the world's highest-level pump efficiency and low noise, is suited to closed-circuit systems, such as HST drive systems, in industrial vehicles.

†† The M7V Series, a hydraulic motor with the world's highest power density and low noise, is suited mainly to HST drive and winch winding systems in industrial vehicles.

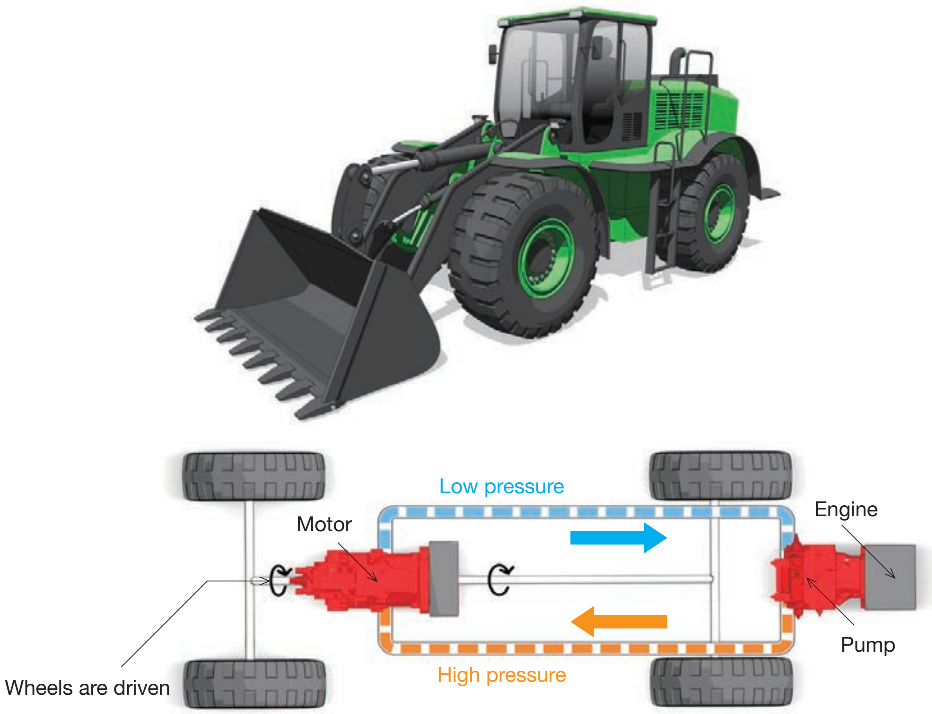


Fig. 1 HST system

## 2 Specifications

Generally, hydraulic pump and motor sizes are classified according to the displacement, and the K8V series offers a lineup of three different sizes, while the M7V series offers a lineup of four different sizes. **Table 1** and **Table 2** shows the specifications of the K8V series and M7V series. Both series have high-pressure specifications for use with HST, and the M7V series has high-speed specifications.

## 3 Features

**(1) K8V series**

(i) High efficiency

The efficiency of the latest flagship pump is improved by performing prior verification, including accurately grasping the internal behavior and conditions, with advanced measurement technologies and simulations. This has allowed the K8V series to achieve the world's top-class efficiency. As shown in **Fig. 2**, the K8V series has high efficiency especially in the high-pressure region, higher than a competitor's pump by up to 4 points.

(ii) Low noise

The noise level of the latest flagship pump is improved significantly by means of simulation and analysis, and the noise level of the K8V series has been improved in the same way. For example, the K8V125 has a sound power level of 89 dB (A) when the displacement is 125 $cm^3$, the pressure is 15 MPa, and the pump speed is 2,100 $min^{-1}$, lower than a competitor's pump by 2 dB (A).

**(2) M7V series**

(i) Improvement of maximum speed and stability at low speeds

In improving the maximum speed, particular attention

Table 1 Specifications of K8V series

| Model code | | K8V71 | K8V90 | K8V125 |
|---|---|---|---|---|
| Displacement〔$cm^3$〕 | | 71 | 90 | 130 |
| Pressure〔MPa〕 | Rating | 42 | | |
| | Max | 50 | | |
| Rated speed〔$min^{-1}$〕 | | 3, 300 | 3, 050 | 2, 850 |

Table 2 Specifications of M7V series

| Model code | | M7V85 | M7V112 | M7V160 | M7V212 |
|---|---|---|---|---|---|
| Displacement〔$cm^3$〕 | q max | 68 to 88. 5 | 90 to 112 | 128 to 160 | 172 to 215 |
| | q min | 0 to 68 | 0 to 90 | 0 to 128 | 0 to 172 |
| Pressure〔MPa〕 | Rating | 42 | | | |
| | Max | 50 | | | |
| Maximum speed〔rpm〕 | at q max | 3, 900 | 3, 550 | 3, 100 | 2, 900 |
| | at $q_1 < 0.6q_{max}$ | 6, 150 | 5, 600 | 4, 900 | 4, 600 (0. $4q_{max}$) |

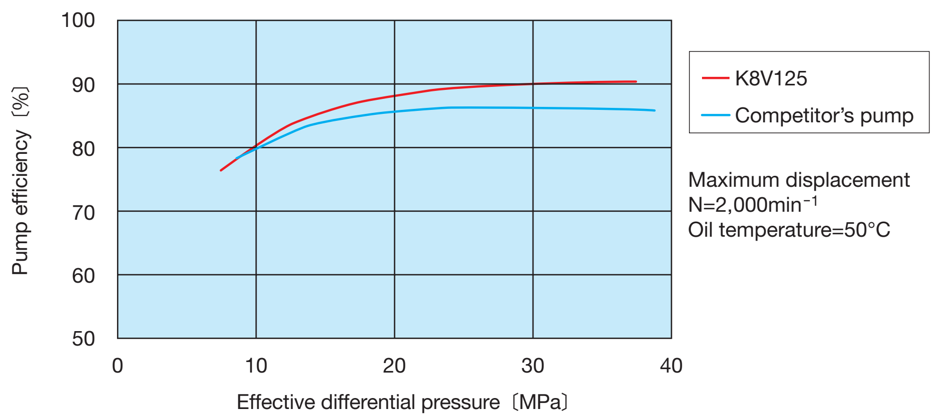


Fig. 2 Comparison of pump efficiency

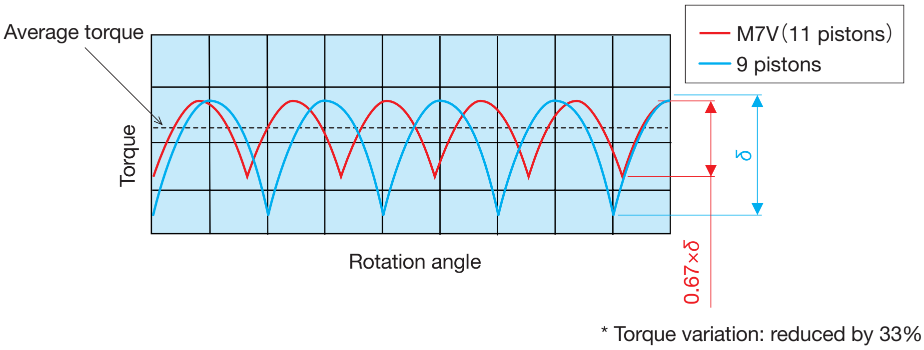


**Fig. 3 Torque fluctuations with the motor rotation**

must be paid to the heat generated in sliding parts. Heat transfer and fluid analyses were used to design the M7V series to reduce heat generation and release heat, thereby doubling the maximum speed from the conventional model.

Stability at low speeds is affected by torque fluctuations, which depend on the number of pistons on the high-pressure side while the motor is rotating. The number of pistons has been increased from 9 to 11, thereby achieving stable rotation at low speeds with reduced torque fluctuations, as shown in **Fig. 3**.

(ii) Low noise

The M7V series uses a high-rigidity swash plate type design to reduce vibration, which causes noise, and adopts noise reduction technology as the pump does, thereby achieving low noise. For example, the M7V85 has a sound power level of 89 dB (A) when the displacement is 51 $cm^3$, the pressure is 10 MPa, and the motor speed is 6,150 $min^{-1}$, lower than a competitor's motor by 4 dB (A).

## Conclusion

The K8V series and M7V series have been developed as the culmination of Kawasaki's latest technologies. We will be expanding the sales of these series so more and more customers will be able to benefit from their excellent features.

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# KGPR65D – High-pressure Hydrogen Regulator for Fuel Cell Vehicles


*Fuel cell vehicles are drawing attention as eco-friendly vehicles, and in order to stably supply hydrogen to fuel cells—which are the vehicles' power sources—high performance regulators are being required. We have developed a small, reliable, high precision regulator that can firmly seal hydrogen gas for about 20 years, a vehicle's lifespan, based on the fluid control technology that has been developed through our many years of developing and manufacturing hydraulic devices. And the regulator was highly rated by Daimler and adopted for the mass production of the fuel cell vehicle Mercedes-Benz GLC F-CELL.*

## Introduction

As awareness of global environmental problems is increasing, it is necessary to make efforts to reduce greenhouse gases to zero for the future.

## 1 Background

Electric vehicles and fuel cell vehicles (FCVs) are drawing attention as eco-friendly vehicles that are replacing gasoline-powered vehicles. These new types of vehicles work not only as a means of transportation but as energy sources in the event of a disaster. An FCV is a vehicle powered by a motor driven by electricity that a fuel cell generates by causing oxygen from the air to chemically react with hydrogen on-board. FCVs are known as more environmentally friendly than gasoline-powered vehicles and feature shorter refueling time and longer range than electric vehicles.

The majority of the current FCVs use an on-board system that has hydrogen in a super high-pressure gas state of 70 MPa (700 atmospheres, but up to 87.5 MPa at high temperatures) and reduces the pressure of the hydrogen causing it to react with oxygen in the fuel cell.

Based on the fluid control technology that Kawasaki has developed through its many years of developing and manufacturing hydraulic devices, we have developed a regulator that precisely turns the super high-pressure gas into a gas of the order of 1 MPa.

## 2 Product Overview and Specifications

The high-pressure hydrogen regulator KGPR65D has been integrated into a unit of a regulator valve that regulates gas and a pressure relief valve that automatically relieves the gas to the outside to protect downstream devices when the controlled pressure becomes abnormal. System configuration of a general fuel cell vehicle is shown in **Fig.1**, the outside view of the high-pressure hydrogen regulator KGPR65D is shown in **Fig. 2**, and its major specifications are shown in **Table 1**.

## 3 Features

Hydrogen is the lightest and smallest substance as indicated by the fact that it is the first element in the periodic table. So, it has specific features such that it may degrade mechanical characteristics by penetrating metal materials (hydrogen embrittlement) and it easily leaks as it can permeate even rubber molecules.

So, for metal, since high-strength materials cannot be used as they are easily subject to hydrogen embrittlement, the necessary strength is secured by refining shapes of parts and paths based on strength analysis.

And the seal portions have been designed to endure

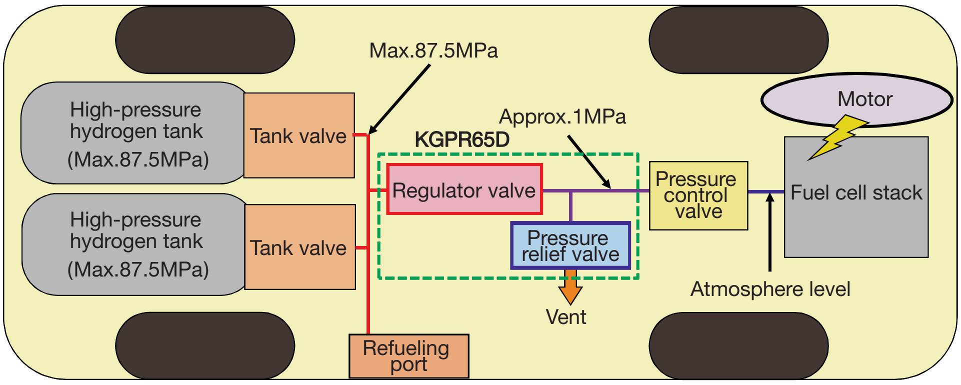


**Fig. 1 System configuration of fuel cell vehicle**

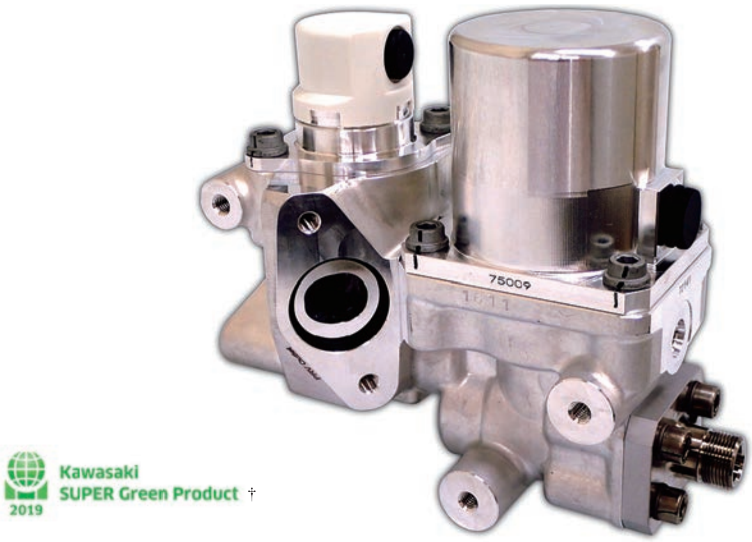


**Fig. 2 High-pressure hydrogen regulator KGPR65D**

super high-pressure by refining their materials and shapes and are manufactured in a highly precise manner in terms of the dimensions of their metallic parts and surface roughness by taking advantage of technology developed through manufacturing hydraulic devices.

From the above, this product is capable of sealing high-pressure hydrogen gas over a wide range of temperatures from −40°C to 85°C without requiring any maintenance for 20 years, which is a vehicle's lifespan.

† The KGPR65D, a hydrogen regulator with high-precision gas control, contributes to achieving zero $CO_2$ emissions of running fuel cell vehicles (FCVs).

Table 1  Major specifications

| | |
|---|---|
| Inlet pressure range〔MPaG〕 | 2. 0 to 87. 5 |
| Regulator control pressure〔MPaG〕 | 0. 9 to 1. 4 |
| Rated operating flow rate〔g/s〕 | 1. 6 |
| Operating temperature range〔°C〕 | -40 to +85 |
| Pressure relief valve working pressure〔MPaG〕 | Approx. 2. 0 |
| Mass〔kg〕 | Approx. 1. 9 |

**(1) Small and highly precise**

This product can instantly reduce the pressure of gas from an extremely high-pressure to a pressure of approx. 1 MPa (10 atmospheres), allowing it to be made smaller than a product that gradually reduces the pressure in multiple steps. This technology is based on the fluid control technology fostered through the development of defense products about 40 years ago and has been improved and evolved over time.

As shown in **Fig. 3**, the product is designed so that its moving parts that adjust the orifice opening for pressure reduction are supported by ball bearings isolated from the hydrogen gas atmosphere, offering highly precise pressure adjustment capability as well as durability that can endure for the lifespan of a vehicle.

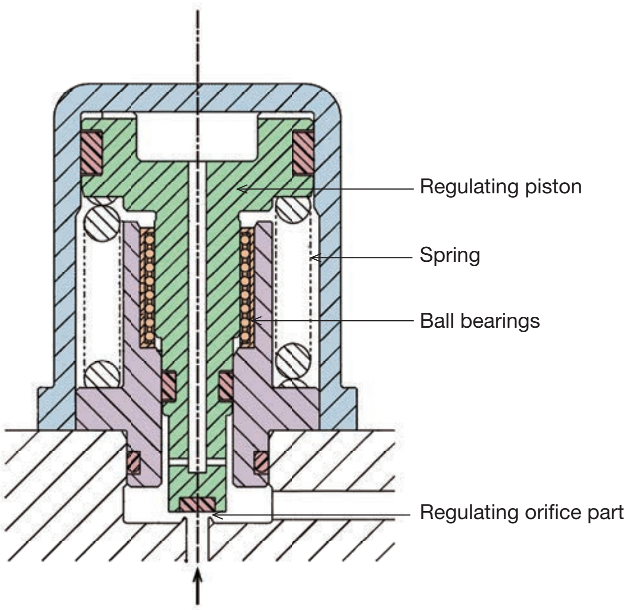


Fig. 3  Construction of regulator


Fig. 4  Fuel cell vehicle Mercedes-Benz GLC F-CELL

**(2) Highly reliable**

To drive an FCV on public roads, the vehicle must basically be certified in the respective countries or regions. This is because it is necessary to maintain safety when a vehicle that has installed hydrogen gas compressed at an extremely high-pressure runs close to us.

Such certification requires various types of testing such as vibration and shock, temperature humidity cycle, pressure cycle, and operation durability, and they all assume a vehicle lifespan of 20 years. European certification requires 14 test items including hydraulic cycle test requiring three times the number of cycles of the assumed load, and North American certification requires 17 test items including fracture resistance test against 2.5 times or higher the maximum inlet pressure to be carried out with a certifying officer from a certified third party organization being present.

In addition, this product has passed all the various reliability tests of about 25 items that German-based Daimler AG independently requires their suppliers to pass.

## 4 Adoption

The high-pressure hydrogen regulator KGPR65D has been adopted for the mass production of the fuel cell vehicle Mercedes-Benz GLC F-CELL shown in **Fig. 4**, and we have started delivering the regulator from January 2018. This FCV is now being sold only in European markets but is going to be marketed in Japan as well in the future.

## Conclusion

This regulator won a mobility related department award of the Super MONOZUKURI (manufacturing) Parts Grand Prize at MONOZUKURI Nippon Conference in 2018 held by NIKKAN KOGYO SHIMBUN, LTD. Since hydrogen is an environmentally friendly energy source, we will continue developing new products and delivering them to the market to "create new value-for a better environment and a brighter future" as in our group mission.

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# N-ECST – Controller for Variable Speed Control Pump System


*It has been a long time since energy-saving equipment and systems were made commercially available for the first time in the hydraulic market, but the demand for greater usability and functionality is still increasing. To meet this demand, Kawasaki has developed an innovative new controller, which greatly improves the performance and functions of controllers used to control position, pressure, and other parameters by feedback control, for ECO SERVO, an energy-saving hydraulic pump speed control system.*

*With the latest control technology, this new controller enables automatic control gain tuning, and provides drastically improved performance and operability with newly added functions effective for multi-axis control and newly commercialized application tools that facilitate maintenance.*

## Introduction

With increasing attention being given to environmental and resource issues due to global warming, various kinds of equipment and systems that take energy saving into consideration have been made commercially available in the hydraulic market over the years. Amid such circumstances, energy-saving products have been applied in an increasingly wider range of fields, and therefore, the demand for greater usability and functionality has been increasing.

## 1 Background

Kawasaki has released ECO SERVO as an energy saving product for hydraulic systems. ECO SERVO is a system that drives a hydraulic pump with a servo motor to control the flow rate required for actuator operation based on the hydraulic pump speed, which enables the minimum required power to be output, thereby achieving significant energy saving.

As for controllers, which play a key part in ECO SERVO's system, the demand for simplification of tuning work, cooperative control of multiple actuators, and visualization of operation states has been increasing. Kawasaki has developed N-ECST—a new controller with drastically improved performance and operability compared with conventional products.

## 2 Specifications

N-ECST has a feedback control function to calculate the optimum hydraulic pump speed for the operation state. Hydraulic pump speed control requires feedback control for the device being controlled as shown in **Fig. 1** to precisely control the force (pressure) and position of the actuator. The dotted line indicates the control range of N-ECST.

**Table 1** shows the specifications of N-ECST and a conventional product. N-ECST has enhanced control performance and enables multi-axis control with automatic control gain tuning and faster control calculation, which are based on the latest control technologies. Also, N-ECST has achieved improved usability through the use of the communication function and compliance with standards.

## 3 Features

**(1) Automatic adaptive control**

Expanding on simple adaptive control (SAC), Kawasaki

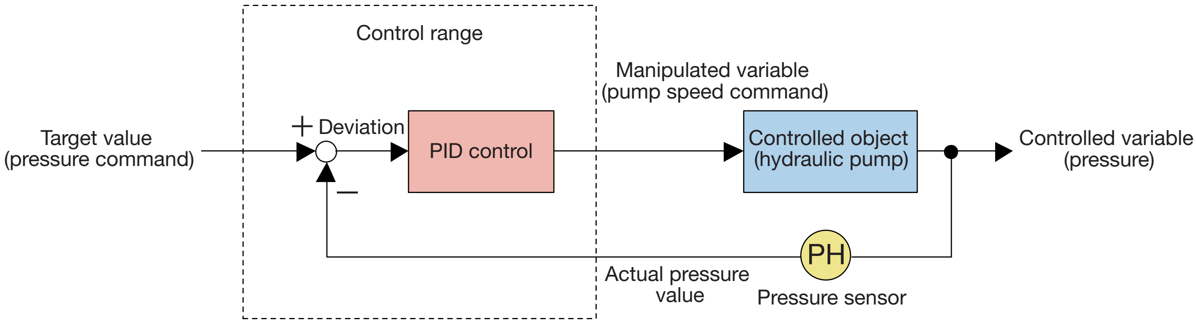


**Fig. 1  Configuration example of feedback control**

**Table 1  Specifications of N-ECST and conventional product**

| Item | N-ECST | Conventional products |
|---|---|---|
| Controlled object | 1 to 4 axes | One axis only |
| Control function | Automatic adaptive control,<br>PID control, etc. | PID control |
| Control cycle | 2ms | 5ms |
| Power supply | DC24V | DC24V, DC5V |
| Communication function | RS232C, Ethernet, CAN | - |
| Applicable standards | CE marking<br>RoHS directive | - |

incorporated its own unique compensation function to provide a new kind of adaptive control that enables stable, responsive adaptation.

N-ECST has an auto tuning function that automatically tunes the control gain with the appropriate response for the load, which reduces the time needed for the machine to start up and provides stable control tuning that is not dependent on the operator. **Figure 2** shows the waveform when auto tuning is applied for position control. The figure shows that the control gain is high at the start but the actual position values gradually converge on the command values.

**(2) Multi-axis control function**

With increasingly higher work efficiency and control accuracy in industrial machinery, the demand for simultaneous multi-axis control is increasing, including back pressure control for multi-axis forming presses and leveling control for lifting and lowering devices and horizontally moving devices, to name a few. To meet this demand, Kawasaki offers two types of N-ECST: one-axis control and two-axis control.

The two-axis control type has an interface for two

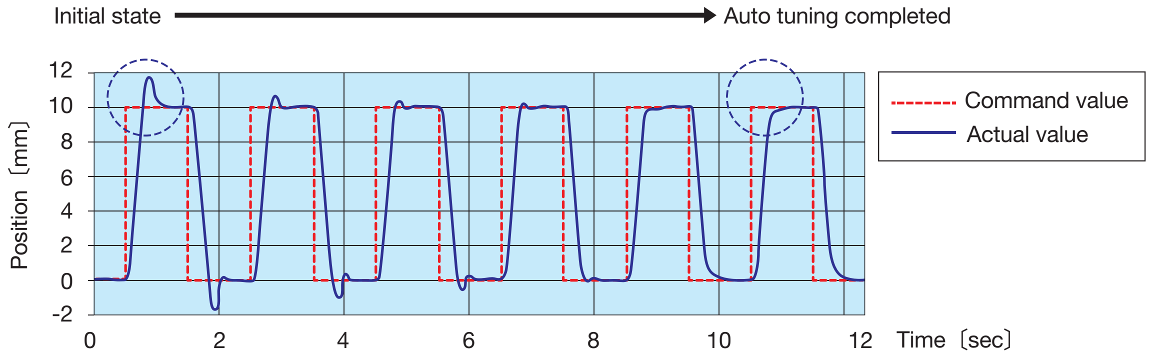


Fig. 2 Waveform with auto-tuning function

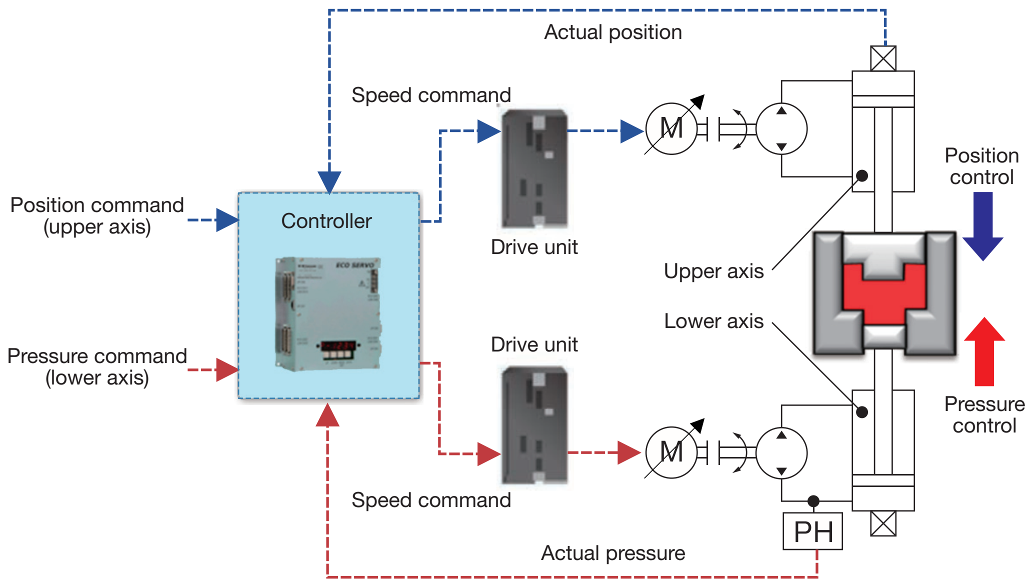


Fig. 3 Application example of two-axis controller

actuator axes and can control two axes individually. When two units are connected, up to four axes can be controlled precisely and cooperatively.

**Figure 3** shows an example of application of the two-axis controller to a multi-axis forming press. The state of each axis mutually interferes with press operation, but the two axes are controlled simultaneously with one controller, enabling highly responsive compensation control. While the upper axis is lowering to press a workpiece at the position control speed, the lower axis is performing high-precision back pressure control (cushioning), contributing to stable forming.

**(3) Enhanced maintenance function**

To achieve high-precision control, quantitative data analysis is required. N-ECST is equipped as a serial LAN communication function as standard along with application software for internal control variable data checks and real-time graph display. In addition to command values and actual values, such as pressure, position, and pump speed, control operation data can be displayed in real time.

To handle an increased number of control parameters with an increased number of functions, N-ECST is provided with a parameter control tool that makes it possible to easily change parameter values. N-ECST can be connected to a user's PC for easy operation, contributing to improved usability and reduced man-hours.

N-ECST has been used to tune machines installed overseas and monitor their condition remotely from Japan by connecting N-ECST to the machines via the internet.

## Conclusion

N-ECST has been building a track record mainly in the press field and automotive parts field. Kawasaki will be working to enhance usability and to apply N-ECST in a wider range of fields with an optional communication function that is compatible with industrial networks currently being developed.

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## Kawasaki Heavy Industries Group
## Main Products and Production Bases by Business Segment

| Business Segment | Main Products | Main Production Bases |
|---|---|---|
| Ship & Offshore Structure | • LNG carriers, LPG carriers, crude oil carriers, bulk carriers, container ships, car carriers, high-speed vessels, submarines, ships for government and municipal offices | Kobe Works (Kobe, Hyogo Prefecture)<br>Sakaide Works (Sakaide, Kagawa Prefecture)<br>Nantong COSCO KHI Ship Engineering Co., Ltd. (China)*<br>Dalian COSCO KHI Ship Engineering Co., Ltd. (China)* |
| Rolling Stock | • Train cars, integrated transit systems, freight cars | Hyogo Works (Kobe, Hyogo Prefecture)<br>Harima Works (Harima-cho, Hyogo Prefecture)<br>Kawasaki Motors Manufacturing Corp., U.S.A. (U.S.A.)<br>Kawasaki Rail Car, Inc. (U.S.A.) |
| | • Rotary snowplows, de-icing vehicles<br>• Rail cars, heavy lift cars | NICHIJO CORPORATION. Head Office (Main Plant)(Sapporo, Hokkaido)<br>Akebono Plant (Sapporo, Hokkaido) |
| Aerospace Systems | • Aircraft (fixed-wing aircraft and helicopters), missiles, electronic equipment, space systems and peripheral equipment, simulators | Gifu Works (Kakamigahara, Gifu Prefecture)<br>Nagoya Works 1 (Yatomi, Aichi Prefecture)<br>Nagoya Works 2 (Tobishima-mura, Aichi Prefecture)<br>Kawasaki Motors Manufacturing Corp., U.S.A. (U.S.A.) |
| | • Aircraft components, target systems, rocket components, space equipment, remodeling | NIPPI Corporation Aerospace Division<br>(Yokohama, Kanagawa Prefecture) and<br>Aircraft Maintenance Division (Yamato, Kanagawa Prefecture) |
| | • Aircraft engines<br>• Aircraft gear boxes | Akashi Works (Akashi, Hyogo Prefecture)<br>Seishin Works (Kobe, Hyogo Prefecture) |
| Energy System & Plant engineering | • Gas turbine engines for ships<br>• Gas turbine generators, gas turbine cogeneration systems | Akashi Works (Akashi, Hyogo Prefecture)<br>Seishin Works (Kobe, Hyogo Prefecture) |
| | • Steam turbines, diesel engines, gas engines, large decelerators<br>• Marine propulsion systems (side thrusters, steerable thrusters)<br>• Natural gas compression modules, air blowers and other aerodynamic machinery | Kobe Works (Kobe, Hyogo Prefecture)<br>Harima Works (Harima-cho, Hyogo Prefecture)<br>Wuhan Kawasaki Marine Machinery Co., Ltd. (China) |
| | • Air conditioning equipment, general-purpose boilers | Kawasaki Thermal Engineering Co., Ltd. Shiga Works<br>(Kusatsu, Shiga Prefecture) |
| | • Cement, chemical, conveyers, and other industrial plant systems<br>• Industrial boilers for land and marine use<br>• Waste treatment facility<br>• LNG tank and other storage facilities<br>• Shield machines, tunnel boring machines | Harima Works (Harima-cho, Hyogo Prefecture)<br>Shanghai COSCO Kawasaki Heavy Industries<br>Steel Structure Co., Ltd. (China)*<br>Anhui Conch Kawasaki Equipment<br>Manufacturing Co., Ltd. (China)*<br>Anhui Conch Kawasaki Energy Conservation Equipment<br>Manufacturing Co., Ltd. (China)*<br>Shanghai Conch Kawasaki Engineering Co., Ltd.* |
| | • Crushers, environment-related equipment | EarthTechnica Co., Ltd. Yachiyo Works (Yachiyo, Chiba Prefecture) |
| Motorcycle & Engine | • Motorcycles, ATVs (all-terrain vehicles), recreational utility vehicles, utility vehicles, Jet Ski watercraft<br>• General-purpose gasoline engines | Akashi Works (Akashi, Hyogo Prefecture)<br>Kakogawa Works (Kakogawa, Hyogo Prefecture)<br>Kawasaki Motors Manufacturing Corp., U.S.A. (U.S.A.)<br>Kawasaki Motores do Brasil Ltda. (Brazil)<br>India Kawasaki Motors Put. Ltd. (India)<br>Kawasaki Motors Enterprise (Thailand) Co., Ltd. (Thailand)<br>PT. Kawasaki Motor Indonesia (Indonesia)<br>Kawasaki Motors (Phils.) Corporation (Philippines)<br>Changzhou Kawasaki and Kwang Yang Engine Co., Ltd. (China)* |
| Precision Machinery & Robot | • Hydraulic equipment for construction machines, hydraulic equipment and systems for industrial machines<br>• Marine application machines, deck cranes and other marine deck equipment<br>• Industrial robots<br>• Medical and pharmaceutical robot | Akashi Works (Akashi, Hyogo Prefecture)<br>Nishi-Kobe Works (Kobe, Hyogo Prefecture)<br>Kawasaki Precision Machinery (U.K.) Ltd. (U.K.)<br>Wipro Kawasaki Precision Machinery Private Limited (India)<br>Kawasaki Precision Machinery (Suzhou) Ltd. (China)<br>Kawasaki Chunhui Precision Machinery (Zhejiang) Ltd. (China)<br>Kawasaki (Chongqing) Robotics Engineering Co., Ltd.<br>Flutek, Ltd. (Korea) |
| | • Hydraulic presses | Kawasaki Hydromechanics Corp. (Akashi, Hyogo Prefecture) |

*Affiliated company-equity method

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**Kawasaki Green Product Promotion Activity**

To achieve our group mission, “Kawasaki, working as one for the good of the planet,” we promote Kawasaki Green Products and Kawasaki Super Green Products inside and outside Kawasaki. These products meet the criteria originally established by Kawasaki to assess the conformity of products regarding environmental performance and environmental management in manufacturing processes.

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