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.

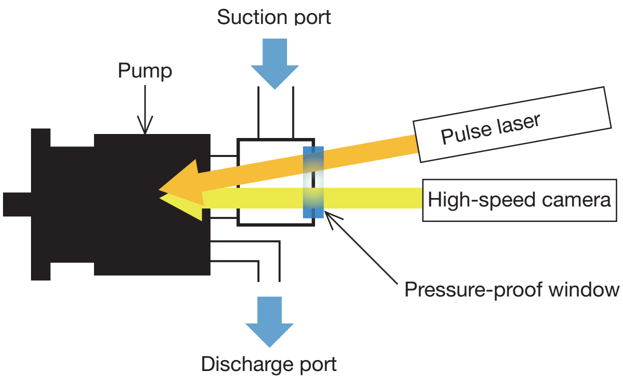


Fig. 3 System for observing cavitation bubbles in hydraulic pumps

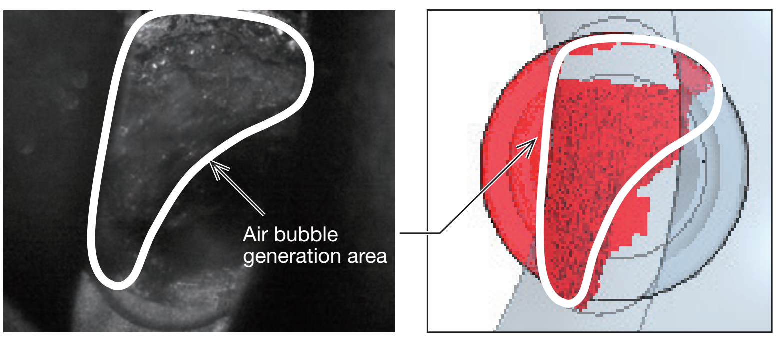
4 Hydraulic system evaluation bench HILS

(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

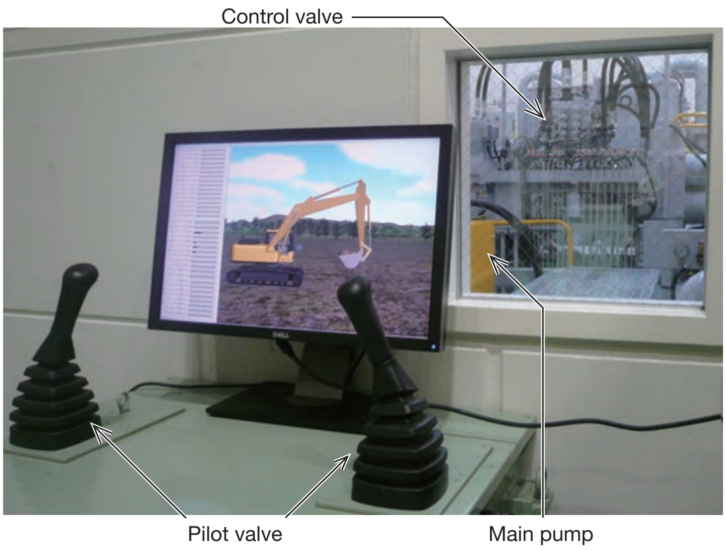


Fig. 5 Evaluation bench for hydraulic systems HILS

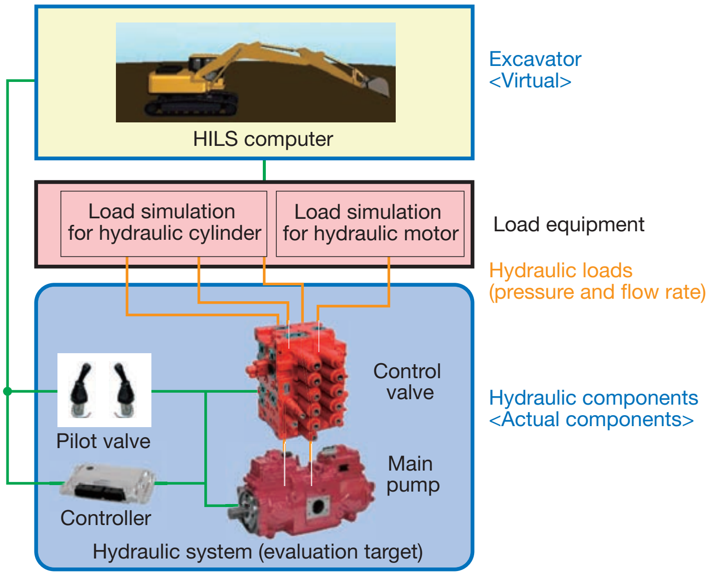


Fig. 6 Configuration of HILS

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.

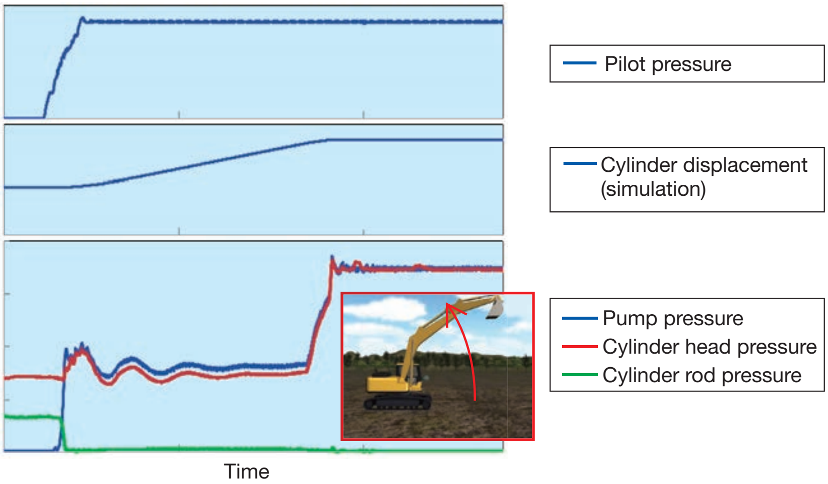


Fig. 7 Example of HILS operation (response to boom-up operation)

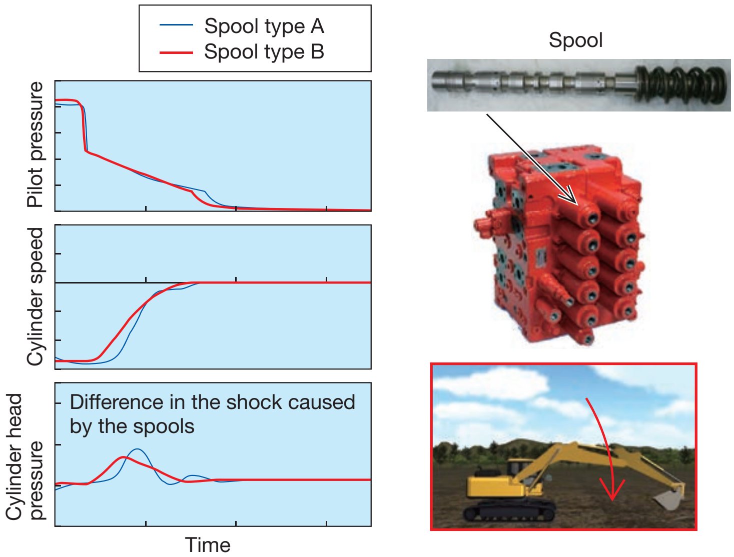


Fig. 8 Evaluation of operability with HILS (shock behavior when the boom stops moving down)

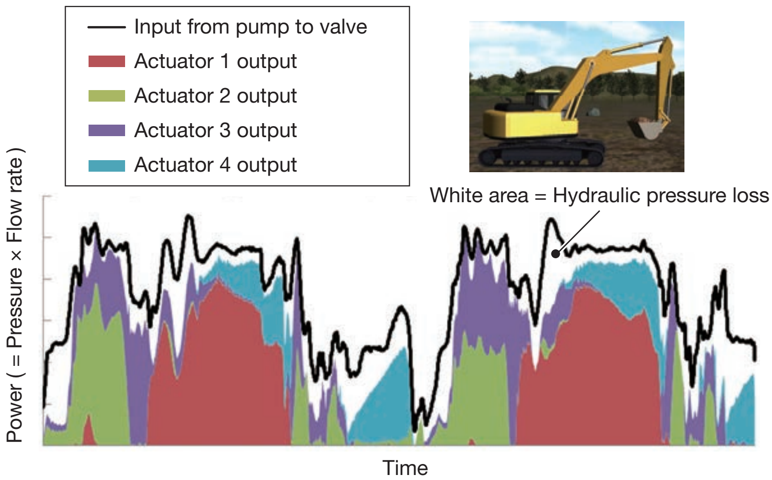


Fig. 9 Evaluation of efficiency with HILS
(Power balance of control valve at digging and loading operation)

(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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