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Numerical Simulation and Experimental Validation of the Hydraulic L-Shaped Check Ball Behavior

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Abstract**—**The spring-driven ball-type check valve is one of the most important components of hydraulic systems: it controls the position of the ball and prevents backward flow. To simplify the structure, the spring must be eliminated, and to accomplish this, the flow pattern and the behavior of the check ball in L-shaped pipe must be determined. In this paper, we present a full-scale model of a check ball made of acrylic resin, and we determine the relationship between the initial position of the ball, the position and diameter of the inflow port. The check flow rate increases in a standard center inflow model, and it is possible to greatly decrease the check-flow rate by shifting the inflow from the center.

Keywords**—**Hydraulics, Pipe Flow, Numerical Simulation, Flow Visualization, Check ball, L-shaped Pipe.

I. INTRODUCTION

HYDRAULIC systems are used for work that requires linear and rotational motion, large forces, and freely changeable speed, and the advancement of hydraulic technology has allowed it to be used as a means of energy transfer not only in construction and civil engineering equipment but also in products more closely associated with our daily lives such as automobiles, airplanes, and elevators. One of the important components of a hydraulic system is the check valve. Most check valves that use a ball also generally use a spring to push on the ball to regulate its position to reliably prevent back flow. There is a strong desire, however, to eliminate the spring because of the problem of it being broken by the chattering of the ball and to reduce costs. In addition, the shapes of the piping used around the check valve are the straight type and the L-shaped elbow type. Testing and analytical research are being conducted on the shape of the straight type check valves [1], [2]. Further, research, eigenvalue analysis, and three-dimensional numerical analysis, etc., are being conducted on poppet valves [3]. The simulation method of fluid power systems is developed and discusses several analysis results in detail by comparing simulation results with actual measurement results [4]. Comprehensive reviews of flow-induced vibration can be found in many publications [5]-[9].

The check ball behavior of hydraulic check valves with L-shaped piping in terms of the hydraulic fluid flow and the effect on check ball behavior of that flow, etc., have not been clarified to date. The flow in the pipe applies hydrodynamic force to the ball causing the flow around the check ball to become a more complex flow and bend further to the perpendicular. The behavior of the check ball at this time is subject to the complex relationship between flow path relative position relationship and the flow rate, viscosity, and other factors. For this research we used transparent acrylic models of actual check valves to observe the check valve behavior while respectively changing the ball position, flow rate, and viscosity and to study the check ball behavior and the check flow rate at which the check valve can reliably prevent back flow. For the models we used three types with different inlet positions in diameter and as the test pieces. Please note the when the check ball in the hydraulic pipe was used as a check valve, the pressure difference was made small and the model was made of acrylic to provide good visibility.

II. EXPERIMENTAL APPARATUS AND METHOD

The example of the usage of the check ball of hydraulic check valves with L-shaped piping is shown in Fig. 1. Cushions are small diameter pistons (6) that enter a small cavity (2) machined into the end caps. Cylinder heads with cushions usually have a built in check valve (5) that allows the free flow of hydraulic fluid into the cylinder so that the speed of the cylinder will not be limited when the direction of travel is reversed. Cylinders with adjustable cushions will have needle valves (4) mounted in the heads so that the flow of fluid leaving the cushion can be adjusted and the amount of deceleration can be tuned for the application.

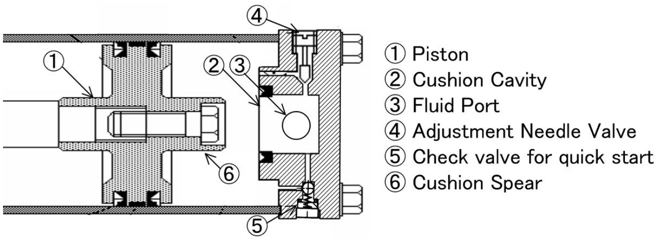

Fig. 1 Schematic view of dumper cylinder

A schematic diagram of the test apparatus is shown in Fig. 2. The computer (6) controls the head speed of the servo actuator (7). The hydraulic cylinder (5) is connected to the actuator and operated to determine the flow rate of the acrylic plastic L-shaped pipe sample (1). Pressure of 100 kPa is applied to the hydraulic fluid tank of (9) to prevent air from being sucked into the hydraulic fluid. The test confirmed the check ball rises and can be checked, and the 300 fps high-speed camera of (4) was used to observe the ball to measure its rotation. Because images were used to measure the rotation, the ball, which was made of

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steel, was marked with six plus (+) laser markers. The test parameters were the initial position of the check ball, the hydraulic fluid kinetic viscosity, and the hydraulic fluid check flow rate. For the model shapes, Center Model, the reference model, uses a 9 mm cylinder in diameter containing a 7.94 mm check ball and allowing inflow via a 2 mm orifice in diameter at the center and outflow via a 5 mm orifice in diameter. Middle model was modified by shifting the inflow position to the half radius side and Side model was modified by sifting to the maximum side sift so that the swirling flow of the hydraulic fluid would cause the ball to rotate. Center model and Middle model are shown in Figs. 3(a) and (b) respectively.

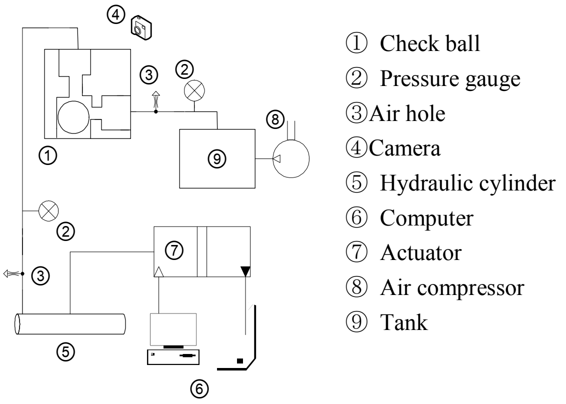
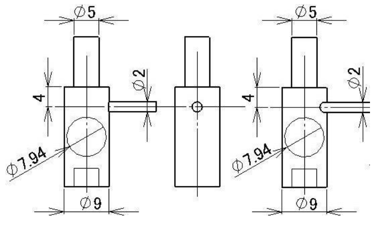


Fig. 2 Experimental apparatus



(a) Center model (b) Middle model

Fig. 3 L-shaped pipe arrangement

The lift amount was determined by regulating the ball bottom position while filming the ball from 2 directions using digital cameras. The check ball initial position was tested using lift amounts of 1, 2, 3, 4, and 5 mm. Hydraulic fluid kinetic viscosity of 5 mm^2/s, which is the general hydraulic fluid range, was used, and the check flow rate was tested in the range of 0 to 60 cm^3/s (0 to 6.0 × 10-5 m^3/s). For the test each of these was conducted 5 times and evaluated by taking the average for the check flow rate and the rotational speed. The effect on the check flow rate and rotational speed of the kinetic viscosity at the respective positions was found, but the detailed state of the flow was unknown. Here, flow beads made by Sumitomo Seiko Chemicals that are low-density polyethylene particles with an average diameter of 11 μm and that have been alumite surface treated were added to the hydraulic fluid, and image processing using a high-speed camera was conducted to observe the flow around the check ball.

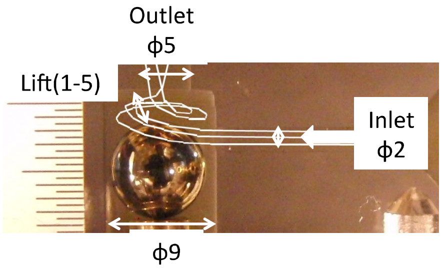
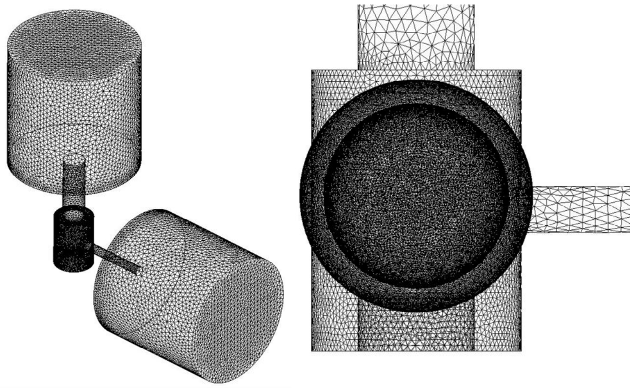


Fig. 4 Experimental model

III. Numerical Simulation

The thermofluid CAE analysis tool SCRYU/Tetra was used for analysis and the state of the flow was observed. A low Re k-ε model was used for the turbulent flow model and a no-slip condition was used for the wall surface condition. Fig. 5 shows an example of mesh arrangement. Eight layers of 1.5×10-4 m thick boundary layer mesh were inserted to improve the resolution of the separation and reattachment in the vicinity of the wall surface, etc. Mass flow rate specification was used for the inflow condition and natural inflow and outflow conditions were used for the outflow condition. For the mesh preparation, the area from the inflow opening to the ball vicinity was observed very carefully and a steady analysis was conducted using an approximately 3 million mesh partition number.



(a) Mesh arrangement (b) Mesh on large scale

Fig.5Mesh arrangement

IV. Results and Discussion

The ball rise as well as the relationship between the checkable check flow rate and lift obtained from the test are shown in Fig. 6. Since the experimental check flow rate was very reproducible and the error was within 5%, the average value for it is shown. The measurements of the check flow rate show not more than a 10% difference, proving the accuracy of the CAE analyses. As can be seen in Fig. 6, for all models, little change is caused in the check flow rate by the change. In the Middle mode, it was found that by shifting the position of the inlet, is added to the swirling flow, it is possible to reduce the check flow rate.

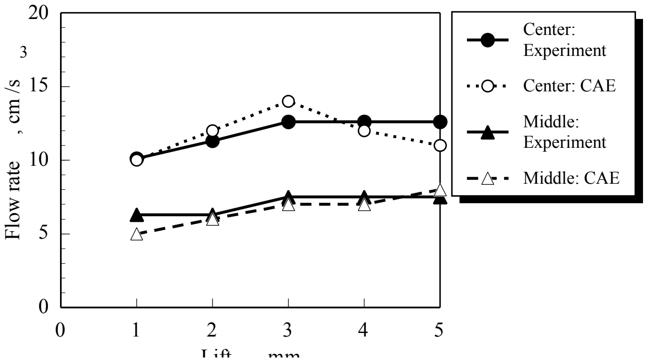


Fig. 6 Relationship between lift and check flow rate

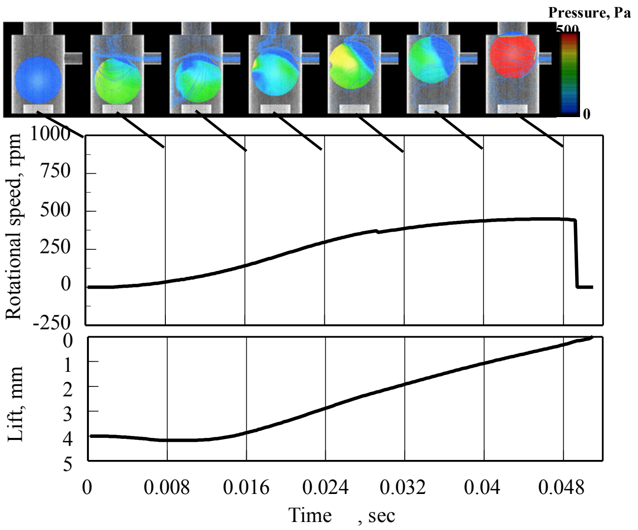


Fig.7 Relationship between the rotational speed and lift of the Center model (12 cm^3/s)

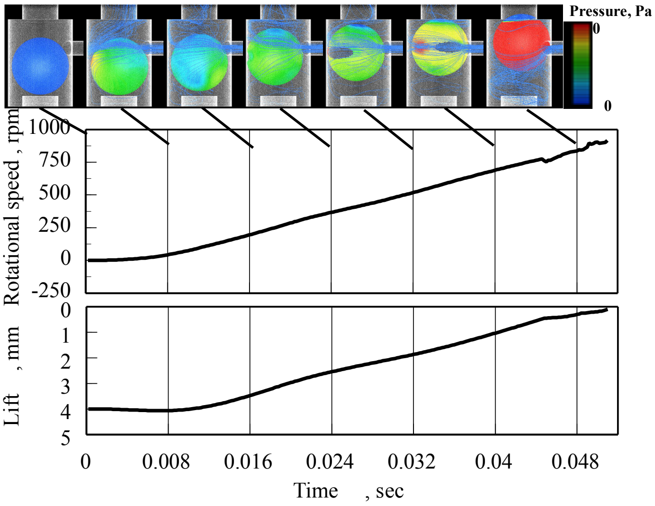


Fig.8 Relationship between the rotational speed and lift of the Middle model (12 cm^3/s)

The CAE results of the rotational speed, lift amount, and flow pattern of a flow rate of 12 cm^3/s of the Center model and the Middle are shown in Figs. 7 and8 respectively. Here the direction of the check ball rotation of Center model is vertical direction. Middle model is oblique direction. The effect on the flow pattern of the difference in inflow position is studied. The flow pattern is shown in top part of Figs. 7 and 8. A swirling flow is not generated in the center model and sedimentation occurs in the corners. In the Middle model, however, a swirling flow is generated and strikes the ball and flows along the ball. We can see there is a large swirling flow in the Middle model with a lift amount of 3 mm or more. In other words, to generate a strong swirling flow, the middle model and side model are good when the lift amount is a relatively large 3 mm, and the side model is good when the lift amount is small at around 2 mm. From the CAE results of flow pattern and ball surface pressure distribution, in the Center model, the pressure at the bottom of the ball is relatively high, and at the top of the ball it is low. In the center model at the lift of 3 or 4mm, the surface pressure is only high at the area directly struck by the jet. The jet strikes the top of the ball more when the lift amount is 4 mm rather than when the lift amount is 2 mm as in Fig.7, which creates a large downward force on the ball. However, comparing the lines of flow shows there is much flowing toward the bottom of the ball. In other words, the direct downward surface pressure on the ball became large, but the flow beneath the ball is generating a force that is acting to push up the ball, which results in little change in the check flow rate.

Using a shape where the inflow is from the side generates a swirling flow and greatly reduces the check flow rate compared to center inflow; making possible a less check flow rate.

CAE is a very useful method for identifying such phenomena as this type of flow and pressure

V. SUMMARY/CONCLUSIONS

The objective of this research is to realize hydraulic ball valves that do not use a spring. There is a strong desire to eliminate the spring because of the problem of it being broken by the chattering of the ball and to reduce costs.A lot of costs are necessary for the experiment for a lot of parameters such as the viscosity of oil, the lift amount, the diameters and the position of inlet. Thus, it is possible to contribute to the reduction in costs of the design if the accuracy of CAE can be guaranteed. Furthermore, it is possible to clarify the phenomenon of interaction of the flow with the ball.Tests were conducted to measure the check flow rate and rotational speed under different hydraulic fluid inflow positions as well as to visualize the flows in the vicinity of the ball.

The results showed that using inflow from the side to actively cause a swirling flow made it possible to raise the ball at low flow rate. However, since the various parameters, such as swirling flow strength, relative position to the ball, inlet position that determines the fluid jet strength, mutual act on each other.

Our main conclusions are summarized as follows.

1) Changing the flow rate and lift while studying the check flow volume showed there is a mutual relationship among the check flow rate, and ball initial position.
2) Using a shape where the inflow is from the side generates a swirling flow and greatly reduces the check flow volume

compared to center inflow; making possible a less check flow rate.

3) In the model with center inflow, at a lift of 1 mm or 3 mm the ball rises easily and the check flow volume is small. At a lift of 4 mm, this balances with the force on the ball from the fluid jet to determine the check flow rate.
4) When the inflow is from the side, the ball rotational speed and the strength of the swirling flow become larger.

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