Mechanism of noise generation by cavitation in hydraulic relief valve

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Abstract. In order to clarify the mechanism of noise generation in a hydraulic relief valve, oil cavitating flows in a half cut model of the valve were observed by means of a high-speed camera and were simulated numerically. As the result of image analysis, the fluctuation of cavitation volume is corresponding to the pressure fluctuation of downstream, and the both fluctuations take peaks at frequencies from 1.5 to 2.5 kHz depending on the back pressure. In addition, as the back pressure increases, the frequency of the pressure fluctuation increases and the peak value decreases. These phenomena were also qualitatively reproduced in the numerical simulation.

1. Introduction
The noise of kHz order in a hydraulic relief valve has been often reported in construction machinery. In the tests of using an actual hydraulic relief valves, the noise has been confirmed in the particular conditions of the flow rate and back pressure, and considered to be owing to cavitation. However, the mechanism of the noise generation has not been clarified yet, because the noise occurred unpredictably. Although the operation of the hydraulic relief valve is not disturbed by the cavitation, a problem is the discomfort of construction machine operators by the noise. Early resolution of the noise generation is required to the development of the future hydraulic relief valves. In the present study, oil cavitating flows in a half cut model of the hydraulic relief valve are observed by means of a high-speed camera and are simulated numerically to clarify the mechanism of the noise generation owing to cavitation.

2. Visualization of the oil cavitating flow in the hydraulic relief valve

2.1. Visualization experimental apparatus
The half cut model based on an actual hydraulic relief valve and the outline of a test section are shown in Fig.1. As shown in Fig. 1(a), the half cut model is composed of the sheet, valve and case. In the actual hydraulic relief valve, the pressure rise between the seat and the valve moves the valve to the right. Then, hydraulic fluids pass through a gap between the seat and the valve and flow outside of the case. But, in the half cut model employed in the present study, the valve is fixed. And the gap between
the seat and the valve is adjusted as 100μm by spacers. On the other hand, as shown in Fig. 1(b), the test section is a sturdy structure to avoid the leak flows between an acrylic plate and the half cut model at operating pressure of several tens MPa.

2.2. Results and discussions of the visualization experiment

The oil cavitating flows in the half cut model were captured by the high-speed camera with a long-distance microscope. Capture conditions were respectively the frame rate of 50,000 fps and the shutter speed of 1/330,000. The pump pressure was 20 MPa and the flow speed through the gap was about 100 m/s. The back pressure was changed from 0.07 to 2 MPa in the present study.

Instantaneous images of cavitation in the downstream of the gap for back pressure of 0.07, 0.5 and 2 MPa are shown in Fig. 2. As shown in Fig. 2(a), cavitation develops to the hole of the case by the jetting flow from the gap. As the back pressure increases, the cavitation region decreases as shown in from Fig. 2(a) to (c).

The cavitation region is defined by binarization processing on the basis of the luminance value, and the cavitation volume is calculated in the partial region surrounded by the broken line in Fig. 2(a). A time-series data of the cavitation volume is then obtained from all captured images. Figure 3 shows the results of the fast Fourier transform for the time development of both the cavitation volume and the pressure at the case exit of the half cut model. The fluctuation of cavitation volume is corresponding to the pressure fluctuation. The both fluctuations take peaks at 1.5 and 2.5 kHz for the back pressure of 0.5 and 1.0 MPa, respectively. In the actual hydraulic relief valve, it is observed that the noise occurs depending on the back pressure. Therefore, cavitation is considered to be a cause of the noise generation in the hydraulic relief valve.

3. Numerical simulation of the oil cavitating flow in the hydraulic relief valve

3.1. Numerical model and numerical settings

According to the experiment as described above, the oil cavitating flow in the hydraulic relief valve was simulated by means of the numerical code, in which cavitation is modeled as the source/sink of vapor phase and is represented by the pressure difference from a vapor pressure. Figure 4 shows the two-dimensional numerical model of the valve with axial symmetry. The oil flows from the gap between the sheet and valve to outside of the case. Boundary conditions are uniform flow at the inlet,
convective outflow at the outlet and non-slip condition on the wall of the sheet, valve and case. Two-
dimensional boundary fitted structured mesh is employed and discretized in space by the grid number
of 450x120. Reynolds number is defined as \( \text{Re} = \frac{v_g \delta}{\nu} \), where \( v_g \), \( \delta \) and \( \nu \) are the velocity through the
gap, the width of the gap and the kinetic viscosity, respectively. The cavitation number is also defined
as \( \sigma = \frac{(p_0 - p_v) (\rho v_g^2/2)}{p_v} \). In the present study, flow conditions are \( \text{Re} = 100 \) and \( \sigma = 0.04-0.10 \).

3.2. Numerical results and discussions
Figure 5 shows instantaneous distribution of the volume fraction of oil, velocity magnitude and pressure.

Figure 6 shows the results of the fast Fourier transform for the pressure averaged in space on the
outlet boundary for various cavitation numbers. The pressure fluctuations take peaks at 2, 3 and 4 kHz
for \( \sigma = 0.04, 0.06 \) and 0.08, respectively. As the cavitation number decreases, the peak values of
the pressure fluctuation decrease with increasing peak frequency. These phenomena were observed in the
Figure 6. Results of the fast Fourier transform of the pressure averaged on outlet boundary for various cavitation numbers.

experiment results as shown in Fig. 3. Thus, it is considered that the present numerical simulation could reproduce the oil cavitating flows in the relief valve qualitatively.

Since the vapor pressure of the hydraulic fluid is low, the simulation for $\sigma = 0.10$ corresponds to the experiment for the back pressure of 0.5MPa. However, the peak frequency of 4 kHz in the simulation is higher than the peak frequency of 1.5 kHz in the experiment. Here, comparing the cavitation region in the experiment and simulation results (Fig. 2(b) and Fig. 5(b)), the cavitation region in the simulation is reproduced smaller than that in the experiment. As shown in the Fig. 6(a), the pressure fluctuation in the simulation result for $\sigma = 0.04$, in which the cavitation grows larger, takes peak at the frequency of 2.5 kHz. This peak frequency is corresponding to the peak frequency in the experiment for the back pressure of 1.0 MPa, as shown in Fig. 3(c). Thus, it is necessary to examine the correspondence of the calculation conditions and the experiment conditions.

4. Conclusions
To clarify the mechanism of the noise generation owing to cavitation in the hydraulic relief valve, the oil cavitating flows were experimentally visualized by means of the half cut model and were numerically reproduced. As the results of the image analysis, it was confirmed that the fluctuation of the cavitation volume is corresponding to the pressure fluctuation. Moreover, it was found that the pressure fluctuations take peaks at the frequency of the order of kHz in the particular back pressure conditions. Therefore, cavitation is considered to be a cause of the noise generation in the hydraulic relief valve. On the other hand, in the numerical simulation, as the cavitation number decreases, the peak values of the pressure fluctuation decrease with increasing peak frequency. Although the peak frequency of the pressure fluctuation in the simulation was higher than that in the experiments, the present numerical simulation could reproduce the oil cavitating flows in the relief valve qualitatively.

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