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Cavitation in a spool valve for water hydraulics

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Abstract. Cavitation sometimes occurs serious problems in hydraulic system. The problems become especially obvious in water hydraulic system because of higher saturated vapor pressure of water comparing of that of oil. This study is focused on cavitation phenomenon in a spool valve for Aqua Drive System. A spool valve model was made of transparent acrylic resin for visualization of cavitation phenomenon. Vibration and noise from the model were measured with changing the cavitation number. As a result, the vibration and noise are enhanced for the smaller cavitation number and the larger opening gap of a control port. It is, however, noticed that vibration and noise become large for some specific condition regardless of large cavitation number. It is revealed that these phenomena depend on cavitation type from visualization results.

1. Introduction

Aqua drive system (ADS) that uses tap water as working fluid has been much attention in recent years [1]-[3]. The ADS have some advantages and disadvantages comparing with oil hydraulic system. The most different point between the ADS and oil hydraulic system is working fluid characteristic especially for viscosity and saturated vapor pressure from a practical point of view. Oil hydraulics is easier to prevent leakage, rust, cavitation and to reduce friction than the ADS. On the other hand, the ADS can be supplied more hygienic, more safety, more environmentally-friendly system than oil hydraulics. Their markets are perfectly different for the reasons above. Oil hydraulics is for high-pressure smokestack industries. The demand of ADS is low-pressure fields; food processing machines, medicine and semiconductor manufacturing equipment.

In these driving system, it should be controlled speed, force and flow direction for actuators by spool valves. The spool valve can be realized precisely control them by change the valve stroke which has small flow passage gaps. The water velocity through these gaps is dependent on the differential pressure. The maximum pressure of the ADS is reached at 14×10^6 Pa, in this case, the water velocity is over 100 m/s and the pressure downstream the gap bellows the saturated vapor pressure. Thus, cavitation is easily generated in the ADS because of that water saturated vapor pressure is much higher than that of oil. So,



cavitation is serious phenomenon for the ADS, it occurs some problems; erosion, noise and vibration, performance degradation. A lot of studies on cavitation noise and vibration has been conducted for oil hydraulic components. [4]- [6] Especially for cavitation in a spool valve, most of studies focused on cavitation choked flow by measurement of pressure-flow rate coefficient. [7]- [8] These literatures reported fruitful results for oil hydraulic component, however, there is little knowledge of cavitation noise and vibration in water hydraulic spool valve. So, the authors made and used a spool valve model with transparent acrylic resin for direct observation of cavitation downstream a control port in the model. Cavitation phenomena with some opening gaps and various differential pressures were visualized. [9] The previous our study cannot be clarified how the cavitation affects vibration and noise in the spool model. To grasp the knowledge of vibration and noise in a spool valve for ADS is quite important from the practical viewpoints. From these reasons, this study is focused on revealing noise and vibration originated from cavitation in the model with changing cavitation number. Another section of your paper

2. Experimental Apparatus and Procedure

Figure 1 shows a testing water hydraulic circuit. Tap water was used as working fluid. Water was supplied with a piston pump unit. The water pressure from the pump was regulated by a relief valve and the flow rate was controlled by pump speed. Water flows into a test section through an accumulator, and then goes back into a reservoir under the pump unit. The water flow rate was measured by an ultrasonic flowmeter upstream the model. The pressures upstream and downstream the model, P_1 , P_2 , were measured with pressure sensors individually. Dissolved Oxygen was measured before and after experiment. The maximum differential pressure in this experiment was $\Delta P = 5.0 \times 10^6 \text{ Pa}$. P_1 was changed up to $5.0 \times 10^6 \text{ Pa}$, and the P_2 was changed up to $1.5 \times 10^6 \text{ Pa}$. The cavitation number which is defined by equation (1) was in the range of $\sigma = 0.0196$ - 0.457 .

$$\sigma = \frac{P_2 - P_v}{\Delta P} \quad (1)$$

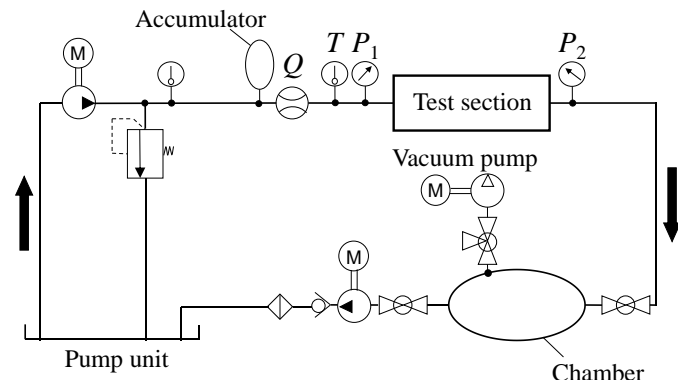
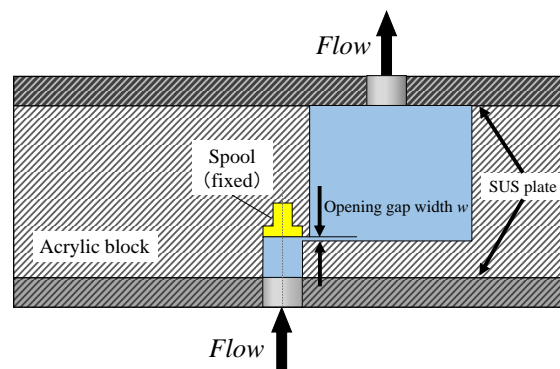
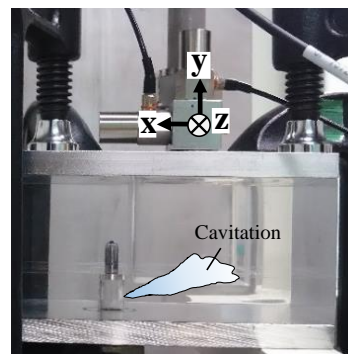
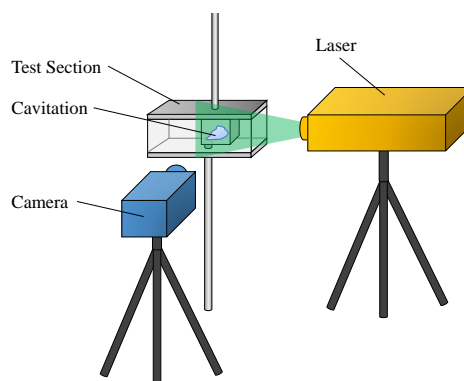
P_v : saturated vapor pressure of working water

Figure 2 shows a detail of the spool model. The model is made of transparent acrylic resin for easy optical access around a control gap in the model. The control gap has a rectangular notch. The notch size is $2 \text{ mm} \times 5 \text{ mm}$ along circumferential and axial direction of the spool. The spool diameter is 12 mm , and the axial gap of the control area was selected three conditions, $w = 0.06, 0.24, 1.05 \text{ mm}$. There is no radial gap between the spool and the sleeve. A 50 mm cubic shape room is downstream the control gap. Noise and vibration from the model was measured with a precision sound level meter (Ono Sokki, LA-3560) and two acceleration meters (Showa Sokki, 2300A).

Figure 3 shows the layout of these acceleration meters for the measurement in x and z direction. The vibration was measured along two of three axis simultaneously. When the noise was measured the model and the sound level meter were in a sound soundproof box to suppress the noise from the pump unit. The sound level meter was fixed with distance of 180 mm from the model. The background noise level was 52.6 dB . Cavitation jet from the control gap was visualized by using a video camera (Lavision, Imager intense) and a pulse laser sheet (Kanomax, DPIV-L50). The sensitivity of the camera is 12bit and the spatial resolution was 1376 by 1040 pixels. The maximum velocity of cavitation jet is up to 80 m/s . The laser emission time is 6 to $8 \times 10^{-9} \text{ sec/pulse}$, this is useful for capturing still images clearly. Arrangement of lighting and viewing area of the camera from the top view of the model is shown in Figure 4.

3. Results and Discussion

Figure 5 shows measurement result of vibration in the direction of y -axis with changing the cavitation number. The trend of vibration was almost same in every direction. The highest vibration was observed along the y -axis which is shown in Figure 5. This result shows that higher vibration occurs for larger opening gap width because of that the vibration magnitude is depend on the cavitation volume.[7] It is also obviously recognized that vibration grows up with decrease of the cavitation number for the same opening gap width. This is because of that cavitation occurs easier for smaller cavitation number. It is noticed that vibration magnitude for $P_2 > 0$ is apparently higher than that for $P_2 = 0$ in case of the same cavitation number.

**Figure 1.** Testing circuit**Figure 2.** Spool model**Figure 3.** Photo of a test section and acceleration sensors for vibration measurement**Figure 4.** Position of laser and camera

Measurement result of sound pressure level with changing the cavitation number are plotted in Figure 6. Higher sound pressure level was observed for smaller cavitation number and wider opening gap. This is the same tendency with the vibration result, thus these noise and vibration were seemed to be generated from the same phenomenon which is originated from the cavitation in the model. In an oil hydraulic relief valve, similar phenomenon were observed. [4]

Figure 7 shows the visualized images in the model downstream the control gap, $w=1.05\text{mm}$ for $\Delta P=4.9 \times 10^6\text{Pa}$, $P_2=0$ or $P_2>0$. Cavitation jet volume variation was visualized for different setting pressure of P_2 . The cavitation jet issuing from the control gap at the lower left in the images. The cavitation volume is strongly dependent on the back pressure. This result was naturally thought from general feature of cavitation. Even if ΔP is the same, increase of the back pressure, P_2 , is reduced cavitation volume compared with that for $P_2=0$. From this observation large bubbles remain for $P_2=0$. In order to focus on the bubble diameter distribution, enlargement images were captured as shown in Figure 8. Figure 8 shows enlargement images that were captured at the location shown as the rectangle in Figure 7 (a). These results suggest that cavitation for $P_2=0$ consisted of cloud and bubble cavitation. The other hand, cloud cavitation was only observed for $P_2>0$. In general the cloud cavitation generates much stronger shock wave comparing with the bubble cavitation. Large bubbles for $P_2=0$ influences suppression of shock wave originated from the cloud cavitation. That is why higher vibration and noise were measured for $P_2>0$.

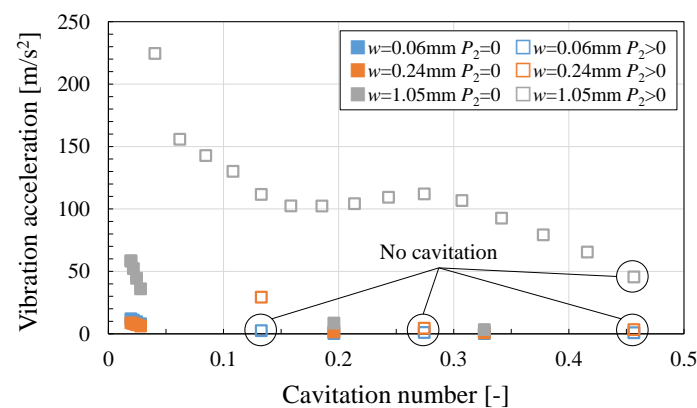


Figure 5. Relationship between cavitation number and vibration acceleration along the y-direction

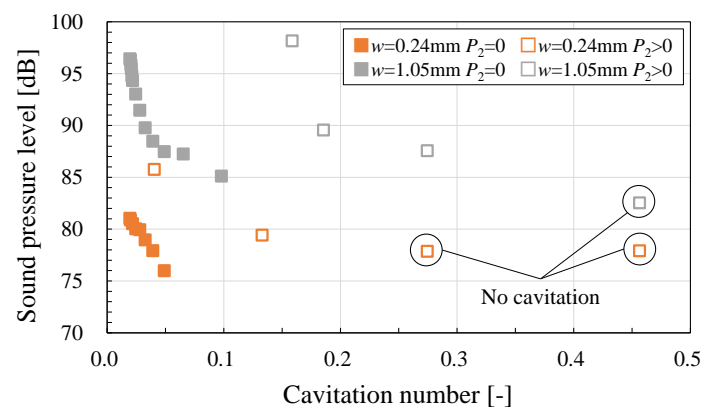
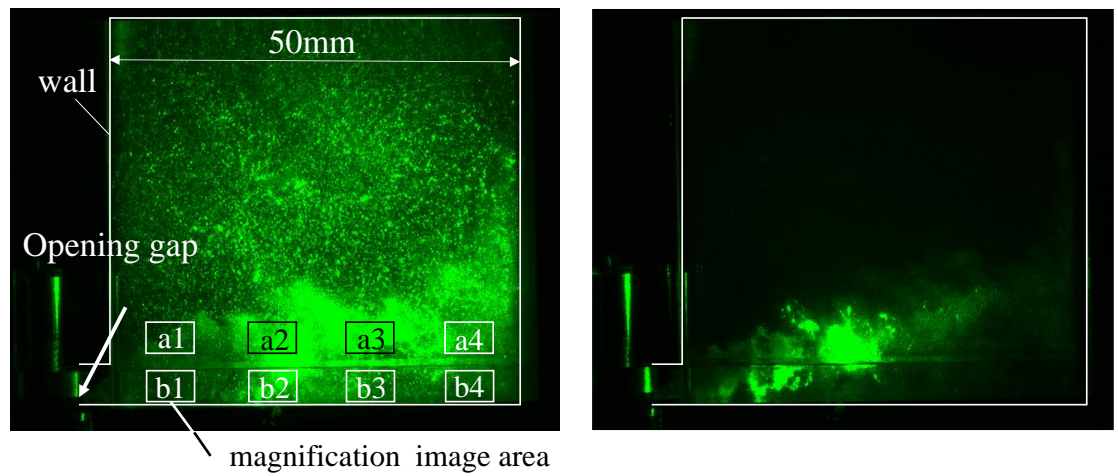


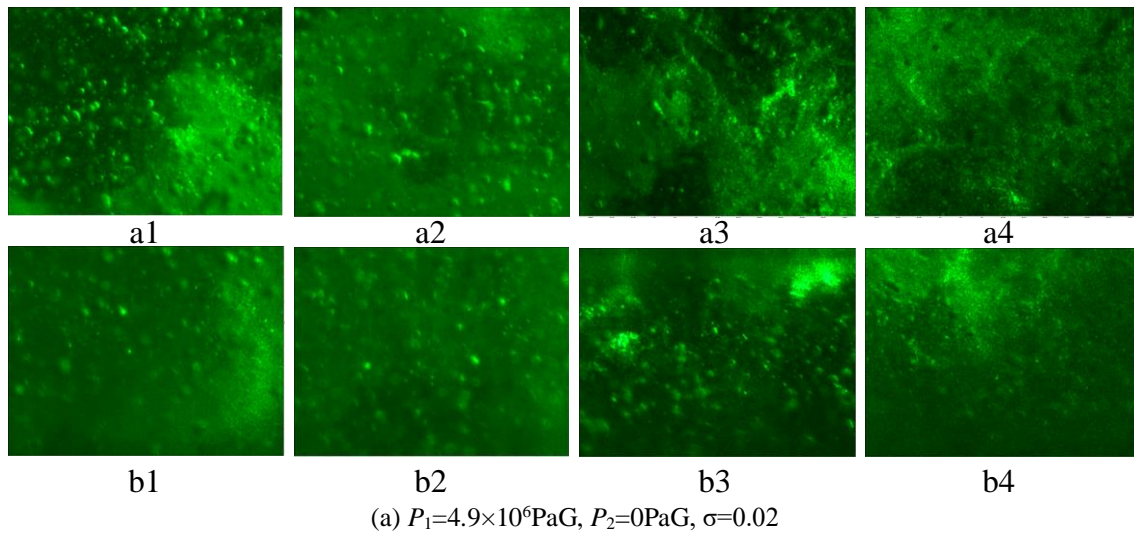
Figure 6. Relationship between cavitation number and sound pressure level



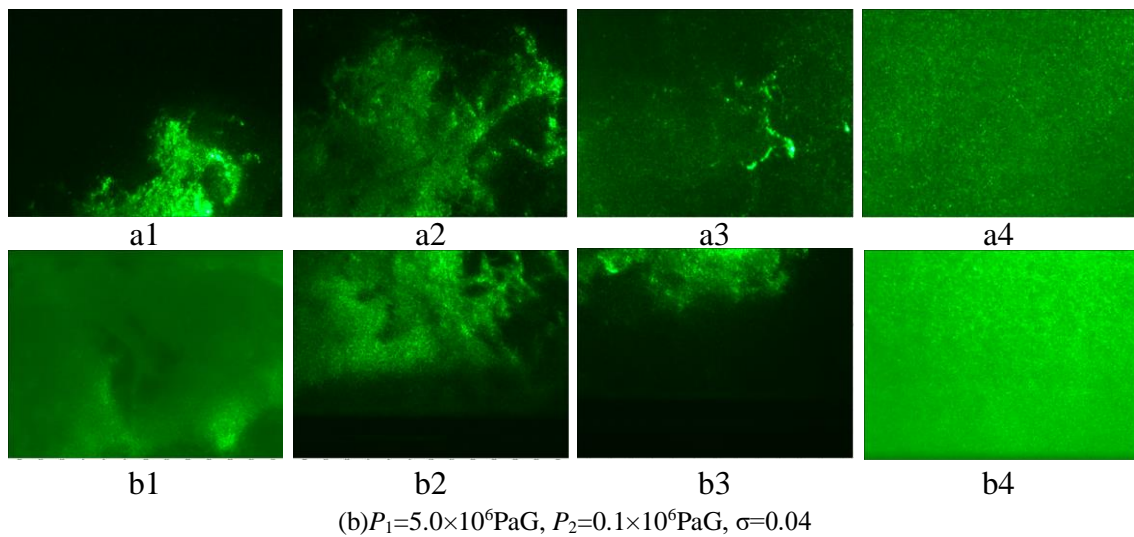
(a) $P_1=4.9 \times 10^6 \text{ PaG}$, $P_2=0 \text{ PaG}$, $\sigma=0.02$

(b) $P_1=5.0 \times 10^6 \text{ PaG}$, $P_2=0.1 \times 10^6 \text{ PaG}$, $\sigma=0.04$

Figure 7. Visualization images of cavitation jet for $w=1.05 \text{ mm}$ $\Delta P=4.9 \times 10^6 \text{ PaG}$



(a) $P_1=4.9 \times 10^6 \text{ PaG}$, $P_2=0 \text{ PaG}$, $\sigma=0.02$



(b) $P_1=5.0 \times 10^6 \text{ PaG}$, $P_2=0.1 \times 10^6 \text{ PaG}$, $\sigma=0.04$

Figure 8. Enlargement images of cavitation jet at each visualization area shown in Fig.6

4. Conclusions

The authors tried to reveal the relationship between the cavitation behavior in a water hydraulic spool valve model and noise and vibration experimentally. The following results can be drawn;

- 1) Higher noise and vibration were generated for smaller cavitation number and the wider opening gap width.
- 2) Cavitation jet pattern issuing from a control gap are changed with cavitation number and the back pressure of the control orifice. Especially for the specific condition which allows only generating cloud cavitation, noise and vibration are enhanced.

Acknowledgement

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