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INVESTIGATION ON CAVITATION BEHAVIOR AND NOISE IN HYDRAULIC VALVES

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ABSTRACT

Cavitations inside hydraulic valves were investigated by using high-speed camera technology and noise spectrum analyzing method. The bubble flow’s morphological and flowing characteristics were converted into numerical information by the employment of image process, which made the two-phase flow easily identifiable. Based on this, cavitation’s distribution and shape characteristics were revealed. Combined with cavitation noise spectrum analyzing, it was found that the shedding process of cavitation had similar high frequency properties with cavitation noise spectrums. Typical noise curves of cavitations were obtained, and the second peak levels were found in low cavitation number conditions. In addition, it assumed that, the shedding frequencies played a good reflection to cavitation noise while using cavitation numbers as the only variable.

KEY WORDS

Hydraulic, Cavitation, Image process, Noise spectrum

NOMENCLATURE

B : the width of groove
Fs : the camera speed
f : the frequency of shedding
h : the depth of groove
L : cavitation bodies’ average length
Lp : Cavitation noise level
l : the length of groove
Re : Renault number
s : Cavitation bodies’ helical pitch
x : the opening of the valve
σ : the cavitation number

INTRODUCTION

Cavitation phenomena are common in various hydraulic components like pumps, valves and cylinders etc. The reason can be explained by the complex channels and high differential pressure. As we know, cavitation causes undesirable problems, such as vibrations, noise and erosions. Many efforts have been taken on the issue and progresses have been made. Vibrations induced by cavitation were investigated by Guoyu Wang [1]. Cavitation's erosion and flow choking phenomena were revealed in Koivula's papers [2]. Moreover, simulations related were conducted with the code of Fluent by Hong Gao [3]. However, Kiesbauer and Vnucec [4] gave a detailed description about cavitation in control valves with axi-symmetrical characteristics. Special threshold points were indicated within a typical cavitation development process, like incipient cavitation, incipient choked flow, maximum noise and the material damage threshold. A typical cavitation noise curve according to ISA standings was presented. And most experimental dates were gained from the medium of water. In Martin's paper [5], cavitation inception characteristics were investigated in oil by pressure energy spectrum method, which seemed to have similar characteristics with the acoustics noise. Camera vision pictures were presented of cone valves in Kiesbauer's paper, but little information was gained. High-speed photography technology and transparent valve body were employed in our experiments (fig.1, fig.2). With this method, cavitation's distribution and shape characteristics can be easily observed. Furthermore, the relationship between cavitation noise and its morphological characteristics was studied. In Sato and Saito's research on orifice cavitation [6], the similar method was taken. Orifices with different lengths and diameters were studied. From the information supplied by the images, the states of cavitation flow can be identified by its shedding, feed-flow characteristics. Ganippa [7] gave another work in orifices with different flow-in angles. The location of cavitation inception and its no axi-symmetrical changes of flow were illustrated.
Non-circular opening spool valves with U-grooves were studied in our research. Unlike most experimental objects, the U-grooves are not axis-symmetrical. Oil was used as the working media. In most symmetrical flow channels, like cone valves and orifices, cavitation always forms at the position of the inlet edges. However, a new cavitation distribution state was found in the bottom of U grooves. Moreover, the bottom formed cavitation seemed quite calm and made lower noise.

EXPERIMENTAL SET-UP

The experimental set-up includes three parts: throttling valves with turning grooves, high-speed photography system and noise detecting instrument (fig.1).

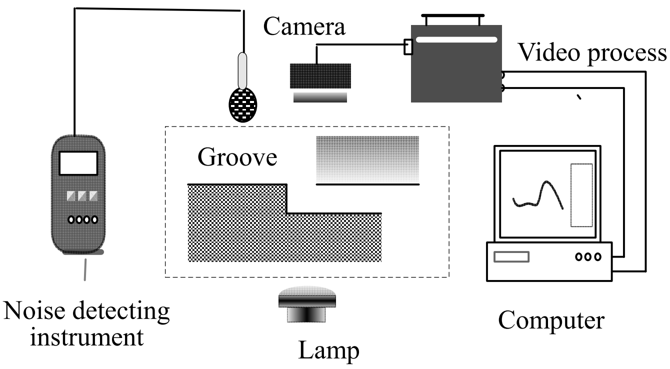


Figure 1 Experiment set-up

The transparent valve body is made of PMMA material (fig.2). All the parameters were the same with the real metallic valve body to keep the original flow state. AWA 6270+ noise detecting instrument was used to gain the noise level and spectrum messages. Cavitation images were taken by FASTCAM-APX 120KC with the maximum speed of 120 000fps. Two photographing direction were used, the front direction and side direction with the angle of 10° (fig.3).

Figure 2 Transparent valve model

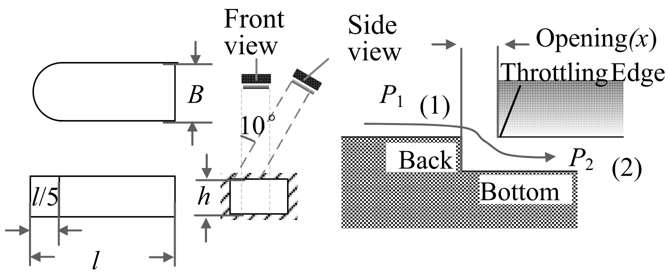


Figure 3 Configurations of the grooves

In this experiment, four types of valve spools of different depths were used. Details of the experimental body were shown in table 1. The four types of grooves had the same width and length parameters, but different depth with the equal depth interval. Different valve openings of 0.3mm, 0.6m, 0.8mm, 1.0mm, 1.2mm, 1.5mm, 1.8mm, 2.0mm, 3.0mm and 3.5mm were studied.

Table 1 Construct parameters of turning grooves [mm]

Valves		U06	U07	U08	U09
Construct parameter	B	2	2	2	2
	l	5	5	5	5
	h	0.5	1.0	1.5	2.0

DISTRIBUTION AND DEVELOPING TREND OF CAVITATION

As we see in fig.3, the oil flow started from area (1), and entered the turning groove, then flow out by the area (2). P_2 varied in an equal interval in the experiment process while keeping P_1 constant. The changing of flow parameters was denoted by the cavitation numbers. Fig.4 showed us that, cavitation appeared in a threshold cavitation number and its body region extended nearly lineally with the continue decrease of cavitation number. Fig.4-6 showed the inception state of cavitation. As we see, cavitation appeared in one side of the groove, which is coincident with Ganippa's findings.

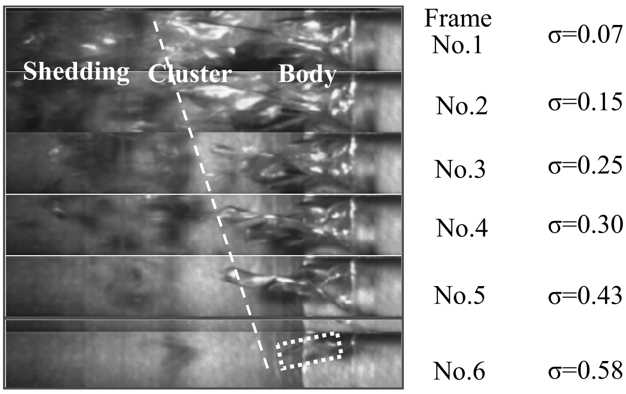


Figure 4 Cavitation's developing Trend

As a typical development process of cavitation, cluster appeared in the body's tail, and then shedding formed, which was referenced from Sato's papers. Cavitation cluster was not quite notable at weak cavitation moments. However, the shedding process always existed in any cases.

As we know, when the local pressure drops down below the liquid's vapor pressure, cavitation incepts. In most cases, cavitation forms near by the entrance edges, like throttling edges of valves and orifices' inlet. At small opening cases in our experiments, cavitation developed under the button of the grooves, which seemed unexplainable by traditional understandings.

The transformation process of cavitation's distribution states were investigated, which seemed regular somehow. Fig. 5-(a) shows cavitation's distribution images in the front view and fig. 5-(b) shows the side view with the angle of 10° in same conditions. The experiment was taken at the cavitation number 0.4 with U07 groove. As we see, in the small opening condition (fig.5-a-3), cavitation developed around the edges formed by the bottom and side faces of the groove looked like the letter of U. As the opening increased, cavitation inception location changed from the bottom of the grooves to the throttling edge. Before the opening reach a threshold value, the letter U distribution state never changed. However, when the threshold reached, the distribution shape transferred from letter U to two radials, and its starting-off location combined with throttling edge. Finally, the two radials hold together to form a single radial (fig.4). As wee in fig.4, the cavitation distribution property didn't change much with the cavitation number as variable. However, the sudden change of distribution state was not found by our ancient studies for the restricting of camera speed.

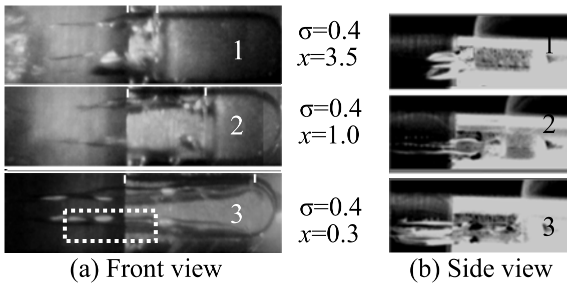


Figure 5 Cavitation distribution states

Many experimental cases were conducted to study cavitation distribution properties and a table was found based on groove's structure parameters. A no dimensional value x/h was used. Since the flow parameters have few influences on the distribution properties, the experiments were conducted in the same cavitation number conditions, σ=0.4. In table 2, the cavitation distribution state-threshold point was remarked with fuscous shadings. In all the U09, U08 and U07 cases, when the value of x/h was less than 1.0, they were cavitation's letter U distribution states, and otherwise were the radial distribution states. It assumed that, the constant value 1.0 of x/h could be used as threshold to distinguish the two distribution states. However, the letter U distribution state never appeared in U06 groove, even the radial distribution state only appeared in sizeable opening cases. When the opening is small, only shedding processes can be found, which may be explained by its shallow groove property. As the liquid flowed by, the turning trend was unnoticeable in the U type valve, and cavitation formed by the throttling edges.

Table 2 x/h =1.0, the threshold of distribution states

valve / opening	U09	U08	U07	U06
0.3	—	0.2	0.3	0.6
0.6	0.3	0.4	—	1.2
0.8	—	—	0.8	—
1.0	—	—	1.0	2.0
1.2	0.6	0.8	—	—
1.5	—	1.0	—	—
1.8	0.9	—	—	—
2.0	1.0	1.3	2.0	4.0
3.0	1.5	—	—	—
3.5	—	—	3.5	7.0

SHAPE AND NOISE CHARACTERISTICS OF CAVITATION

Helix shapes of cavitation body

A typical cavitation development includes three processes, cavitation body, tail cluster and shedding. Most studies emphasized particularly on cluster and shedding characteristics, few researches concerned the cavitation bodies, which seemed to be calm and steady compared with the other two process. However, with the help of the high-speed camera technology, the shape characteristics of the cavitation bodies were made clear. Taking parts view from fig.5-a-3 and fig.4-6, it is easy to find that the cavitation bodies present helix shapes. The bodies' average length L and helical pitch s were used to describe the shape characteristics. It is concluded from the experiment dates that, under the same cavitation number conditions, the average length L and helical pitch s were both getting larger with the increasing of groove depths. There were no noticeable cavitation bodies in the U06 groove. Even in certain cavitation number and structural parameter conditions, the screw interval changed slimly with the passing of time. Furthermore, the changing frequency of the helical pitch seemed to have something to do with cavitation's shedding frequency and noise levels, which will be investigated in our further studies.

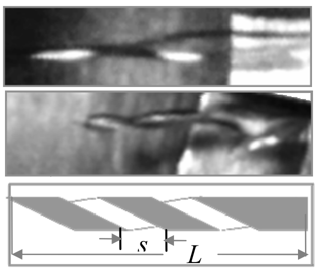


Figure 6
Cavitation bodies' twist shape

Cavitation noise and its periodic shedding process

Typical noise trend with cavitation number as variables was obtained. With the decreasing of cavitation numbers, the noise level raised slowly, however, when cavitation incepted, a sharp rise of the noise level appeared. Until the cavitation number reached its threshold value, the noise came to its maximum and then went down quickly. The similar noise development according to ISA standers was illustrated in Kiesbauer's papers (2006). Second peaks lever (fig.7) were found in the noise curves, and similar trends appeared in Sato's acceleration dates caused by cavitation. As we see in fig.7, the curves of U09 and U08 hold similar characteristics. The average noise level of 0.5mm opening cases in both grooves were quite low than that of larger opening cases, though the opening differences among which were relatively small. However, with the decreasing of grooves' depth, the noise of larger openings weakened, and simultaneously, the smaller ones' get intensified.

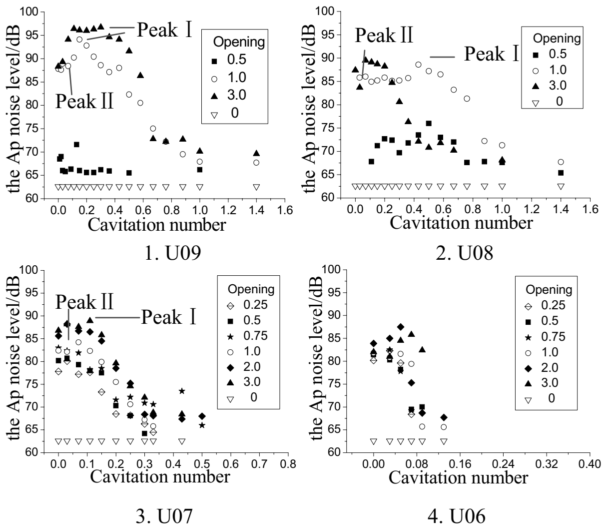
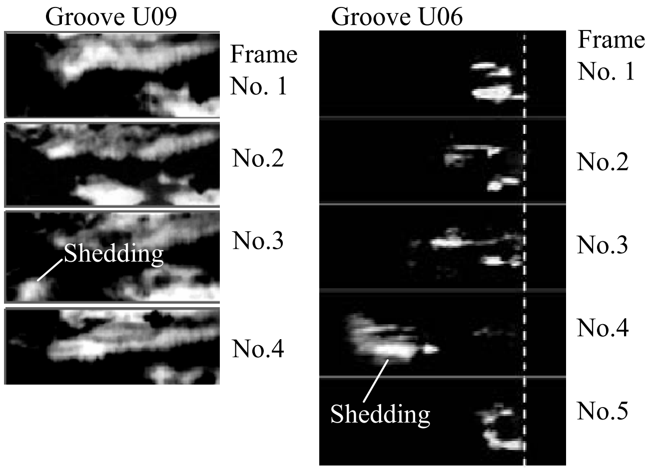
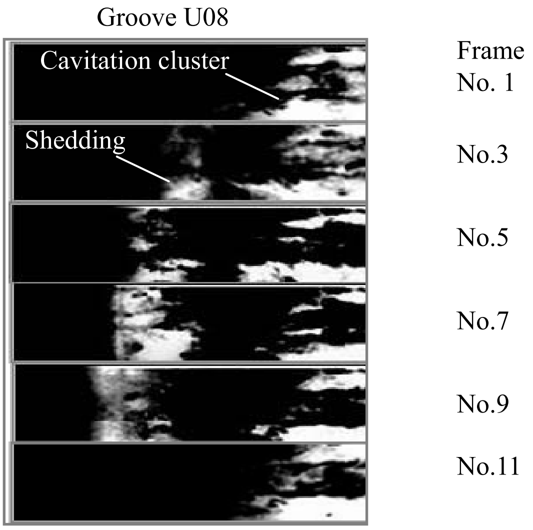


Figure 7 Cavitation noises in different grooves

Periodic shedding processes were studied in Sato's papers, and its relationships with cavitation's re-entrant motion characteristics were revealed. However, the influences of the shedding process on noise were not mentioned. It was concluded from our studies that the shedding frequency reflects cavitation noise to some extent. The shedding periods were obtained by high-speed camera technology and image process. Fig.8 showed the shedding images within one period of three grooves. All the images were taken at their maximum noise condition, while the openings were the same of 1.0mm.



(a) σ=0.15; Fs=40000fps (b) σ=0.05; Fs=40000fps



(c) σ=0.11; Fs=40000fps

Figure 8 Cavitation shedding behaviors

Periods can be calculated by the frame number and camera speed. As a result, $f_{09\text{-}1.0}$=13.3kHz, $f_{08\text{-}1.0}$=4kHz and $f_{06\text{-}1.0}$=10kHz. The high frequency characteristics of the shedding processes seemed to be similar with cavitation noise spectrum, as was illustrated in Christopher's book on cavitation [8]. For the purpose of getting a better understanding of the shedding process, an attempt was conducted. As a continual investigation of groove U09 within 1.0mm opening condition, the shedding frequencies based on different cavitation numbers were figured out, as is showed in fig.9.

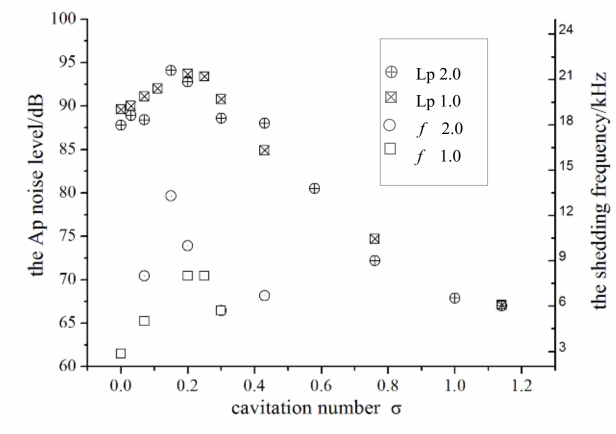


Figure 9 Cavitation noise and shedding frequency

Similar trend of the cavitation noise levels and the shedding frequencies could be seen in this figure. It is reasonable to believe that the shedding frequency could be used as a reflection to cavitation noise. However, with the restriction of camera speed, the frequencies can't be divided detailed, though the highest audible frequency 20kHz can be detected by the current conditions. Moreover, it assumed that the shedding volume also played an important role on cavitation noise, which would be investigated in our further researches.

CONCLUSIONS

(1) Two cavitation distribution states were found in the grooves. And the states' transition threshold point was advanced. It was illustrated that the cavitation distribution characteristics were only effect by structure parameters.
(2) Cavitation's shape characteristics were investigated, the bodies of which exist in liquid environments with helix shapes. The length of bodies extends nearly lineally with the changing of the cavitation numbers. However, no noticeable cavitation bodies, even cluster processes were found in groove U06, though the bodies' average length was getting shorten from groove U09 to U07, which means that there is an appropriate construction for the develops of cavitations.
(3) Cavitation noise was detected in a soundproof room. Typical noise curves were obtained. And moreover, second peck level of noise appeared in the small cavitation number conditions, which is coincident with Sato's acceleration dates on orifice cavitation.
(4) It is illustrated that shedding processes of cavitation exist in any cases, even in groove U06. The shedding frequency was employed to compare with cavitation noise, and similar trends were found within a certain depth and opening condition.

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