A Study on Safety Assessment of a Hollow-Jet Valve Accompanied with Cavitation(キャビテーションを伴うホロージェット弁の安全性評価に関する研究)

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論文内容要旨

CHAPTER 1 Introduction

In most of industrial systems of fluid and energy transport, various types of control valves are utilized to regulate the flow rates in various conditions in pressure, temperature, flow rate and fluid properties. With the development of economic society, more and more big valves are used in industrial, civil engineering and agriculture flow system, for example in water resource dam, civil sewage conduit system and so on. The safety operation of these valves is a very important problem which is related not only to the system safety but also to the human live and life. Among several reasons to induce the valves to become invalid, cavitation, which results in pressure fluctuations, noise, vibrations and erosion, is most serious problem. To avoid such undesirable behavior with valves it is necessary that: (1) to determine the cavitation characteristics of the valve, and (2) to study methods to suppress the cavitation for extending a valve safety operating range. That is, to keep the safety operating of a valve in cavitating conditions, systematic researches on the cavitation around a valve are needed.

To keep the safety operation of a hollow-jet valve in cavitating conditions, this thesis described studies on the cavitation around a hollow-jet valve. The research can be divided into three parts: In the first part, which includes Chapter 2 and Chapter 3, the study was focused on the generation and development mechanisms of cavitation around a hollow-jet valve. In second part, which includes Chapter 4 and Chapter 5, the study was aimed to the phenomena due to the collapses of cavitation cavities, including vibration and erosion. In Chapter 6, the final part of the research, the ventilation effects on cavitation around the valve were studied.

CHAPTER 2 High-Speed Observations of the Cavitation

Two methods were employed to observe the aspects. One was using two high-speed cameras with a xenon flash lamp to photograph the aspects, or a high-speed video camera system to observe and record the continuous aspects. In the second method, a laser light sheet(LLS) was formed in cavitating flow field behind the valve needle, so that the cavitating flow patterns in a LLS section could be observed.

It was found that cavitation bubbles were firstly generated on the needle edge, and then formed a circumference bubble chain behind the needle. So, there were two kinds of cavities which were observed in the cavitating flow around a hollow-jet valve. One was some individual bubbles. Another was some cavitating vortices. In the inception state, more cavities appear as cavitating vortices. With decreasing cavitation numbers, cavitating vortices contained more bubbles, and more individual bubbles also appeared in the cavitating flow. In the subcavitation state, both the numbers of the two kinds of cavities increase with decreasing cavitation numbers. However, in near supercavitation state, more cavities appeared as individual bubbles. In the supercavitation state, a big vapor space was formed behind the needle. With decreasing valve openings, more streamwise bubble chains which connect to circumferencal bubble chains could be observed, which indicates that secondary streamwise vortices also contributed to the formation of cavitating vortices.

The near wake cavitating flow region behind the needle could be divided into three zones: the main flow zone, the shear flow zone, and the vortical separation zone. Cavitation could only be generated in the shear flow zone. In the vortical separation zone, there were a lot of small cavitation bubbles which move with motion of the vortices. Some of the bubbles could flow into the shear flow region, and were entrained by cavitating vortices. So, these bubbles could play the role of active nuclei in the formation of cavitating vortices.

CHAPTER 3 Numerical Simulation of the Unsteady Flow

To make more clearly about the generation mechanisms of the cavitation around a hollow-jet valve, a numerical simulation method was employed to calculate the unsteady flow flied around the valve. The method was proposed by Ikohagi and Shin, which is a kind of modified SMAC scheme. Using this method, the flow field around the valve was simulated successfully.

The computational results show that the formation and shedding of vortices on the edge played a important role in the unsteady characteristic of the whole flow field. The shedding periods of the vortices increased with the valve openings, and decreased with increasing Reynolds numbers. The pressure around the edge decreased in the process of a vortex formation on the edge. It is indicated that, in cavitating conditions, due to the decreasing of the pressure, some bubbles must be formed on the edge, which had been confirmed by the experimental results obtained by high-speed observation in Chapter 2.

CHAPTER 4 Characteristics of the Cavitation Induced Vibration

The vibration was measured in different cavitation conditions using an accelerometer which was mounted on the wall of the test section. The measurement results show that the violent vibration induced by cavitation occurs in the final stage of the subcavitation around cavitation number about 0.55.

By FFT analysis, it can be found that cavitation induced-vibration has its own vibration characteristic frequency band. In this experiment, the sensitive characteristic frequency band was between 10 kHz and 23 kHz. The intensity of cavitation induced vibration changes and correlates well with cavitation number defined in this study. Based on the vibration intensity analysis, the characteristic cavitation number, that is, incipient cavitation number σ_i, critical cavitation number σ_c and maximum vibration cavitation number σ_{mv} are given, and these cavitation numbers are found almost irrespective of the valve openings. According to these cavitation numbers, the development process of cavitation can be divided into three stages: incipient cavitation stage when $\sigma_c<\sigma<\sigma_i$, subcavitation stage when $\sigma_{mv}<\sigma<\sigma_c$ and supercavitation stage when $\sigma<\sigma_{mv}$.

CHAPTER 5 Cavitation Damage Characteristics

The experiments were conducted in different cavitation conditions and valve openings. In each condition, a specimen was exposed the cavitating flow for 80 hours, then specimens were weighted by a digital balance, and the damaged surfaces were observed by a Scanning Electronic Microscope (SEM) at different running times. From the series of experiments, it can be found that he middle cavitation number states, there are more cavitating vortices in the cavitating flow, are the most dangerous for cavitation damage around a hollow-jet valve.

There are two kinds of damage patterns observed on the eroded specimen surface. One is a big plastic crater and/or a wake, which seems due to one blow event by a collapse of cavitating vortex on the specimen surface. Another pattern is an irregular brittle pit, which is induced by cumulative effects of many weaker blows or one single cavity collapse. There are two reasons to make the first kind of crater more erosive: One is that this kind of crater plays a role of damage nuclei in the damage development, and another is that the craters have their size of 100 μ m which is larger than any other damage patterns.

CHAPTER 6 Ventilation Effects on the Cavitation

To find an effective method to suppress the cavitation around the valve, air was supplied to the cavitating area for examining the effects of ventilation on the cavitation. The cavitation aspects were observed with the same methods as these used in Chapter 2. The vibrations of the valve in different cavitation conditions and ventilation amounts were measured. The erosion tests were also conducted under ventilation conditions.

Such a method used in this study as ventilation into the cavitating flow behind the needle of a hollow-jet valve can effectively suppress both the vibration and damage induced by cavitation. The experimental results show that this method can be used to keep the safety operation under cavitating conditions.

The decrease in the intensity of cavitation induced vibration under ventilation conditions is mainly due to the reduction of sonic velocity in the ventilated flow. However, the reasons for the suppression of damage seems more complex. In the ventilation conditions, cavitating vortices contain some air bubbles, and these bubbles can lead mild collapses of the cavitating vortices.

CHAPTER 7 Conclusions

The results and conclusions of the present study are summarized in this chapter.

審査結果の要旨

近年の水源ダム等の水理施設の大型化とともに、流体エネルギーの輸送システムにおける流量調節弁の安全作動範囲を確立することは、防災や市民のライフラインの確保の観点から、ますます重要になってきている。特に、弁のキャビテーション損傷は施設の寿命を短縮し、信頼性を著しく低下させるので、その防止法の確立が切望されている。

本論文は、水深 25m以上の高圧下で放水量 100m^3/s 以下の流量調節弁の一つであるホロージェット弁の相似模型を用いて、弁まわりのキャビテーションの発達過程、これに起因する弁の振動および損傷特性を実験的に明らかにするとともに、自然通気による損傷抑制効果を示し、弁の安全性を評価した研究結果を纏めたもので、全編 7 章よりなる。

第 1 章は緒論である。

第 2 章では、種々の弁開度の下で、キャビテーション係数の低下とともに発達するキャビテーションの様相を瞬間写真と高速ビデオを用いて観察し、その特徴を分類するとともに、ニードル背後の後流中で回流する小径気泡がニードル外周縁からの渦キャビテーションの発生に寄与していることなどを見出している。これらは興味ある結果である。

第 3 章では、ニードルまわりの非定常流れを 2 次元非圧縮性流れで近似し、数値シミュレーションによりニードル外周縁からの渦の放出過程、ニードル背後の渦流れのパターンを可視化し、レーザーライトシート光による高速ビデオ観察結果と対比して、その妥当性を裏付けている。

第 4 章では、キャビテーションが誘起する弁の振動を加速度計により測定し、FFT 解析より 10～23kHz の振動が最も卓越すること、弁開度にかかわりなく振動強さに対する安全性の評価には臨界キャビテーション係数が基準になることを明らかにしている。これらは工学的に有用な知見である。

第 5 章では、ニードルを支える 6 枚のスプリッタの一つを Al 合金の試片とし、キャビテーション損傷による質量欠損の経時変化を明らかにするとともに、走査型電子顕微鏡を用いた損傷面の観察により大規模な塑性クレータと不規則な脆性ピットの損傷パターンを見出し、その形成機構をキャビテーション気泡崩壊の観点から論じている。

第 6 章では、ホロージェット弁の振動強さおよび損傷量がニードル背後へのわずかな通気によって 80%も抑制できることを見出し、これらは主として通気気泡の増加に伴う音速の低下によって壁面に作用する気泡崩壊圧が減少することで説明できることを示している。さらに、これらの抑制が期待できる安全作動範囲を明らかにしている。これらは工学的に有用な成果である。

第 7 章は結論である。

以上要するに本論文は、ホロージェット弁の信頼性に係わるキャビテーションの発達過程と、これに起因する振動ならびに損傷特性を実験的に明らかにするとともに、これらの自然通気による効果的な抑制法を見出したもので、実用のホロージェット弁の安全性を高めることに貢献しており、流体工学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。