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A review of cavitation in hydraulic machinery*

Xian-wu LUO (罗先武)[1], Bin JI (季斌)[2], Yoshinobu TSUJIMOTO[3]
1. Beijing Key Laboratory of CO2 Utilization and Reduction Technology, Tsinghua University, Beijing 100084, China, E-mail: luoxw@tsinghua.edu.cn
2. School of Power and Mechanical Engineering, Wuhan University, Wuhan 430072, China
3. Graduate School of Engineering Science, Osaka University, Osaka, Japan

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Abstract: This paper mainly summarizes the recent progresses for the cavitation study in the hydraulic machinery including turbopumps, hydro turbines, etc.. Especially, the newly developed numerical methods for simulating cavitating turbulent flows and the achievements with regard to the complicated flow features revealed by using advanced optical techniques as well as cavitation simulation are introduced so as to make a better understanding of the cavitating flow mechanism for hydraulic machinery. Since cavitation instabilities are also vital issue and rather harmful for the operation safety of hydro machines, we present the 1-D analysis method, which is identified to be very useful for engineering applications regarding the cavitating flows in inducers, turbine draft tubes, etc. Though both cavitation and hydraulic machinery are extensively discussed in literatures, one should be aware that a few problems still remains and are open for solution, such as the comprehensive understanding of cavitating turbulent flows especially inside hydro turbines, the unneglectable discrepancies between the numerical and experimental data, etc.. To further promote the study of cavitation in hydraulic machinery, some advanced topics such as a Density-Based solver suitable for highly compressible cavitating turbulent flows, a virtual cavitation tunnel, etc. are addressed for the future works.

Key words: cavitating turbulent flow, numerical simulation, turbopump, hydro turbine

Introduction

Cavitation is a very important hydrodynamic phenomenon occurring in many fields associated with liquid transportation. It is well known that hydraulic machinery usually suffers from severe vibration, noise, material damage, etc. due to cavitation. This is the reason why cavitation in hydraulic machinery has attracted our interests for decades.

Hydraulic machinery, such as pumps, hydro turbines, propellers, etc. is widely used in many sectors in our modern society. For examples, turbopumps are utilized in rocket engine system, circulating pumps are used for propellant transportation and heat control unit in a space station[1], 4 rotational ducted propellers and 1 tunnel propeller are utilized for China's first deep manned submersible, Jiao-long[2], the first hydro turbine with huge capacity of 1 000 MW per unit has been developed for sustainable energy supply in the world[3], etc. For those hydraulic machines, the stable and safe operation is critical and should be carefully considered. Based on our experiences, the main causes of damage of hydraulic machinery are due to cavitation problems, sand erosion, material defects and fatigue, etc. Among those causes, cavitation is the most important issue which not only erodes the flow passage, but also induces flow blockage and violent pressure vibration. Generally, cavitation is very harmful to the hydraulic machinery and its system for deteriorating the operation quality and life. Therefore, cavitation has been an active topic for decades in the field of hydrodynamics, and its everlasting progress in mechanism findings and simulation techniques is expected.

To promote the research on cavitation in hydraulic machinery, few scholars summarized the related

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Biography: Xian-wu LUO (1967-), Male, Ph. D., Associate Professor

studies. Arndt[4] tried to show a broad overview based on the state-of-art till 1980. He reviewed the physical phenomena of cavitation, and discussed the factors such as cavitation nuclei, surface roughness, viscosity, etc.. leading to the occurrence of cavitation and its impact on the performance of hydraulic machinery and hydraulic structures. Brennen[5] published a technical book, where unsteady cavitating flows, cavitation induced vibration and dynamic forces in pumps were introduced besides the basic cavitation related principles. Further, Tsujimoto[6] complemented the chapter titled by "Unsteady phenomena in turbomachinery" in the Japanese version, in which the author analyzed 1-D unsteadiness (surge and cavitation surge), 2-D unsteadiness (rotating stall and rotating cavitation), and their interactions in detail. Franc and Michel[7] explained the physical concepts and theoretical explanation for cavitation in their book. The book includes the contents of bubble dynamics and different types of cavitation, and is fairly good for understanding the general nature of cavitation. d'Agostino and Salvetti[8] collected nine lectures related to cavitation in turbopumps, such as the analysis and suppression of cavitation instabilities in turbopump inducers, rotordynamic forces acting on blades, etc..

The reviews for cavitation in hydro turbines are fewer compared with that in pumps. Avellan[9] demonstrated various types of cavity development related to different turbines, and the influences of the operating conditions such as load, head and submergence, etc. on cavitation. Escaler et al.[10] showed the structural vibrations, acoustic emissions and hydrodynamic pressures in several prototype turbines suffering from different types of cavitation. Kumar and Saini[11] discussed various aspects related to cavitation, different causes for the declined performance for the reaction turbines basing on literature survey. Since the draft-tube-surge at part load seriously affects the limit of turbine operating range, extensive studies on the surge have been conducted. Nishi and Liu[12] introduced the related contributions on the following topics: a rational method for component test of a draft tube, nature of spiral vortex rope and its behavior in a draft tube, cavitation induced pressure fluctuations.

In the last two decades, the most remarkable progress must be the challenge of numerical simulation for cavitating flow in hydraulic machinery[13]. The numerical results involving the cavity evolution, vortex shedding, etc. as well as some visualization experiments enable us to have the insight into the nature of various cavitating flows. Though cavitating flows should be computed with a cavitation model based on assumptions, and some discrepancies between calculation and measurement are still observed[14], simulations are considerably helpful to evaluate the cavitating flows and cavitation performance instead of experimental investigations for hydraulic machines during design procedure. Thus, the authors would like to emphasize the recent progress of the study on cavitation in hydraulic machines. Furthermore, the methods for cavitation simulation, and the achievements based on the numerical calculations are focused.

1. Recent progresses for cavitating flow modeling

Most cavitation phenomena involve with turbulence. The numerical accuracy for cavitating turbulent flow simulation depends on both cavitation model and turbulence modeling method.

The present cavitation models in the literature can be classified into two categories: interface tracking and interface capturing procedures. Interface tracking procedures explicitly track and fit a distinct gas/liquid interface, and usually have the limitation to simple problems due to the great numerical difficulties of integrating through the interface for engineering applications. The interface capturing treatment, where the gas/liquid interface is obtained as part of the solution procedure, are more general in their applications and may be applied to both attached sheet cavitation as well as bubbly cavitation[15].

1.1 *Homogeneous mixture flow model*

The mixture cavitation model based on homogeneous flow assumption[16] is one of interface capturing cavitation models, and has been widely applied for the engineering practices in the industry of hydraulic machinery. A typical example of this kind of cavitation model has been developed by Schnerr and Sauer[17], where the physical properties of liquid-vapor mixture are described by Eqs.(1) and (2), and the cavitation process is governed by the mass transfer equation shown as Eq.(3).

The density of liquid-vapor mixture, ρ, is defined by

$$\rho = \alpha_v \rho_v + (1-\alpha_v)\rho_l \tag{1}$$

where the subscript v means the vapor phase, and l means the liquid phase. α is the volume fraction of each phase.

The laminar viscosity of liquid-vapor mixture, μ, is defined by

$$\mu = \alpha_v \mu_v + (1-\alpha_v)\mu_l \tag{2}$$

The mass transfer equation related to cavitation is

$$\frac{\partial(\rho_v \alpha_v)}{\partial t} + \frac{\partial(\rho_v \alpha_v u_j)}{\partial x_j} = \dot{m}^+ - \dot{m}^- \tag{3}$$