



Status of Research on Water Hammer Effect in Long Distance Pressure Pipelines

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JERR/2022/v23i12778

Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: <https://www.sdiarticle5.com/review-history/94406>

Review Article

Received: 06/10/2022

Accepted: 10/12/2022

Published: 17/12/2022

ABSTRACT

In the long distance pressure pipeline, the sudden change of instantaneous pressure caused by the rapid change of liquid velocity is called water hammer, which seriously threatens the safe operation of hydropower station. In this paper, the development and calculation methods of transient flow percussion theory are introduced, and different models and numerical methods are analyzed and compared. Finally, the problems in transient flow research and water hammer prevention measures are summarized, which is helpful to reduce the occurrence of water hammer accidents and guarantee the normal and stable operation of water supply pipeline system. This conclusion can provide reference for water hammer protection of long distance water supply system.

Keywords: Pressure pipeline; transient flowing water strike; numerical simulation; water hammer model.

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1. INTRODUCTION

Pressure pipes are an important part of pumped storage power plants, which introduce water from the reservoir forebay into the turbine under pressurized conditions to meet power generation requirements [1]. In recent years, with the increase of hydropower plant scale and the construction of high-head hydropower plants, the HD value of pressure steel pipes in hydropower plants has grown rapidly, making the strength and stiffness requirements of pressure pipes very demanding, and their stability problems are particularly significant. Especially when the hydroelectric power station pressure pipeline valve suddenly opens and closes, because of the short opening and closing time, the flow rate changes quickly, the water hammer pressure increases instantly, resulting in excessive negative pressure in the pipeline generates cavitation, so that the turbine operation produces vibration, the quality of power supply decreases [2]; in serious cases, it also leads to insufficient strength of the pipeline and rupture, collapse, leakage and other hazards. The hydroelectric power station pressure piping is shown in Fig.1. Since the force characteristics of pressure pipelines are related to the normal use and safety of hydropower plants, it is important to optimize the engineering design and ensure the smooth operation of long-distance transmission pipelines by calculating the pressure and flow velocity of water hammer more accurately and selecting economical and reasonable water hammer protection measures. At present, although the transient flow theory as a whole has been quite perfect, but there are still many problems remain unsolved or need further research.



Fig.1. Hydroelectric power station pressure piping

2. THE DEVELOPMENT OF TRANSIENT RUNNING WATER STRIKE THEORY

In the 19th century, many scholars started to study the vibration characteristics of pipes. Water

hammer theory was first established by the wave propagation mechanism, and its research history has been hundreds of years. In 1858, the Italian engineer Menabrea carried out a study on the phenomenon of water impact, and put forward the theory of elastic water hammer and the use of fluid compressibility and the elasticity of pipe materials to derive the formula for calculating the wave velocity, which has since laid the theoretical foundation of elastic water hammer [3]. Kortweg [4] first considered both pipe wall elasticity and liquid elasticity to determine the water hammer wave velocity in 1878. In 1883, Gromeka [5] first considered the loss of friction in the calculation of water hammer. 1898 Joukowski [6] first proposed the magnitude of water hammer pressure and opening and closing the valve ephemeral law, but also put forward the concept of direct water hammer, indirect water hammer; at the same time, through a large number of water hammer experiments. Gave a direct water hammer pressure calculation formula, the formula is known as the "basic equation of water hammer". In the same year, the American engineer Frizell gave the equation of water hammer pressure about wave speed and flow velocity change [7].

In 1903, Allievi [8] pointed out that the convection term in the kinetic energy equation could not be ignored and established the basic differential equation of unsteady flow. In 1913, Allievi [9] proposed the famous water hammer chain equation, water hammer diagram curve and the final phase water hammer calculation formula, which made outstanding contributions to the calculation of indirect water hammer. However, this theory was widely used in the early 1930s because it was limited to simple pipes with negligible friction. In 1926, Wood proposed the graphical method on the basis of his predecessors, which ushered in a new breakthrough in water hammer theory [10]; subsequently, Schnyder, Bergeron, Lowy, Parmakian, Angus and others [11] refined the graphical method and applied it to complex pipelines. The eigenline method was first proposed by Gray [12] in 1953 to calculate water hammer, and the method is still used today. The principle of the characteristic line method is: to establish a set of curves in the $x-t$ plane, along this set of curves will be the partial differential equations of water hammer into ordinary differential equations, the solution of this set of ordinary differential equations is the solution of the partial differential equations, by the known

points R and B, the unknown quantity P point of the head and flow velocity can be found. The characteristic line method interpolation grid is shown in Fig. 2 [13].

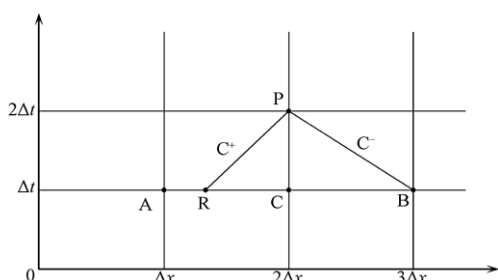


Fig. 2. Characteristic line method interpolation grid

Note: The abscissa Δx represents a unit length, m ; the ordinate Δt represents a unit time step, s ; A, B, C, and P are all schematic points on the grid, and R represents interpolation point; $C+$ and $C-$ represent two characteristic lines

After 1960s, with the popularization of computers, Wylie and Streeter et al. [14] proposed an electrical algorithm based on the eigenline method, which greatly improved the accuracy of water hammer calculation. Subsequently, "Hydraulic Transient" and "Fluid Transient" were published, and the theory entered the computer age. In the early 1980s, many scholars also successively used computer technology to study the full characteristic curve of pumps and water hammer in pumping stations, all of which achieved fruitful results. 1995, Wang Xuefang, Ye Hongkai and others published "Water Hammer in Industrial Pipelines", which solved the common water hammer problems in engineering [15]. 2004, Jin Cone and others wrote "Stop Pump Water Hammer and Its Protection", which explored the water hammer in the problem of water column separation and then bridging [16]. Since the establishment of water hammer theory, the water hammer phenomenon in long distance pressure pipeline has been the focus of attention. The theory has been improved on the basis of hydraulics and fluid mechanics, and has basically satisfied the hydraulic transition calculation in large hydropower station projects.

3. THE CURRENT STATE OF RESEARCH ON WATER HAMMER CALCULATION METHODS

The theoretical calculation of water hammer can be divided into: analytical method, graphical

method and numerical simulation. Among them, the analytical method is mainly based on the Allievi water hammer chain equation to solve the simple pipeline water hammer pressure ignoring friction, for solving complex pipeline has great limitations [17]. The graphical method is based on the analytical method, using fluid velocity and water hammer pressure as the x-axis, y-axis variables to depict the fluctuation process of water hammer waves in turn, compared with the analytical method is more intuitive image, but due to the tedious graphing and accuracy is not high, the method is only widely used in the middle of the twentieth century [18]. With the popularity of computers, the graphical method gradually retired from the historical stage, and a new field, numerical simulation, was introduced. Compared with the analytical method and the graphic method, the numerical simulation method is more accurate and accurate. Numerical simulation technology has low cost, high efficiency, and can simulate complex water hammer conditions, and has been widely used in pumped storage power stations.

3.1 Overview of Numerical Simulation

Numerical simulation mainly includes: the characteristic line method, CFD simulation method, implicit finite difference method, finite element method, etc. [19]. The characteristic line method first discrete the set of water hammer differential equations into a set of difference equations and then calculate, is the basic method for solving partial differential equations, easy to calculate, high accuracy and good convergence, can calculate complex boundary conditions, widely used in the hydraulic transition [20]. CFD simulation method for pipeline water hammer fluid-solid coupling and multi-dimensional water hammer numerical simulation analysis is not yet mature, simulation of water hammer attenuation of the law of change is not effective, has limitations. Implicit finite difference method in solving the differential equations with good stability, can obviously present the law of change of water hammer, but in solving the nonlinear system of equations is too complex [21]. The finite element method is a numerical method for solving unknown quantities by discretizing a continuous solution domain into an ensemble of units, which has a wide range of applications and is the mainstream method in the future.

3.2 Research History of Computational Methods

In non-constant flow, water hammer in the form of ascending and descending pressure waves in the pressure pipe reciprocating motion, which leads to pipe vibration; and the vibration of the pipe affects the fluid motion, and the two interact with each other. The interaction between these two different forms of motion is called fluid-solid coupling [22]. However, the theory of fluid-solid coupling was only gradually accepted by scholars after the 1960s. Subsequently, Liu Zhuxi et al. [23] studied the full characteristic curve of the pump, successfully applied the computer technology and characteristic line method to the water hammer calculation project of hydropower station, and published the monograph "Water Hammer and Its Protection in Pumping Stations" in 1988. Zhu Geqi et al. [24] discussed the vibration characteristics of complex pipes under fluid-solid coupling and pointed out that the generalized complex mode theory has good applicability in studying the vibration response of pipes. Iakis and Selmane applied the Sander thin shell and potential flow theory to study the self-vibration characteristics of pipes [25]. Suo Lisheng et al. have done a lot of work on hydraulic transition of pressure diversion system, which provides theoretical guidance for the later application of pressure regulating chamber in engineering [26].

Zhang Lixiang and Huang Wenhui used Hamilton's variational principle and N-S equation of fluid motion to establish a 4-equation model with axial and lateral displacements, flow velocity and pressure variables, which can describe the nonlinear fluid-solid coupling vibration of the diversion pipeline [27]. Since the 4-equation model is a simplified linear model based on the N-S equation and the FSI basic equation, there are similar 8-equation models and 14-equation models, among which the 4-equation model is used by most researchers. Sun Sujuan used the characteristic line method to solve and calculate the water hammer based on the one-dimensional non-constant flow equation system, and prepared a calculation program using MATLAB, which is empirically feasible [28].

In recent years, Yu Shurong et al. [29] used ANSYS Workbench to analyze the pipeline for single and two-way fluid-structure coupling, respectively, and finally found that the two-way fluid-structure coupling was significantly larger than the one-way fluid-structure coupling. Cao

Yinping et al. [30] used ANSYS Workbench to build a finite element model of the completion pipe column and explored the inherent frequency and vibration pattern of the model under the effect of internal pressure and fluid-structure coupling. In the same year, Dai Zi Han, Tan Ying, et al. [31] analyzed the pressure fluctuation and vibration of a pipeline when a water strike occurred in an open pipe by comparing the characteristic line method with the finite element and finite volume hybrid method of fluid-solid coupling, using the hybrid method of N-S equation and solid line elasticity equation. The results show that the water strike intensity is proportional to the pipe length, inversely proportional to the valve closing time, and also proportional to the fluid flow velocity but the magnitude of the effect is not significant.

Li DD et al. [32] carried out numerical calculation of concrete pump station by using characteristic line method with the help of computer program, and found that the combination form of air container and overpressure relief valve could eliminate the water hammer phenomenon caused by water column separation in pipeline system. This conclusion provides useful guidance for water hammer protection of hydropower station. Subsequently, Wang Xingtao, Zhang Jian et al. [33] established a mathematical model of the air vessel based on the characteristic line method, and improved the installation mode of the air vessel considering the burst of underground pipes, showing that the new installation mode of the pressure vessel can effectively reduce the water hammer pressure. The mathematical model of pressure vessel is shown in Fig. 3.

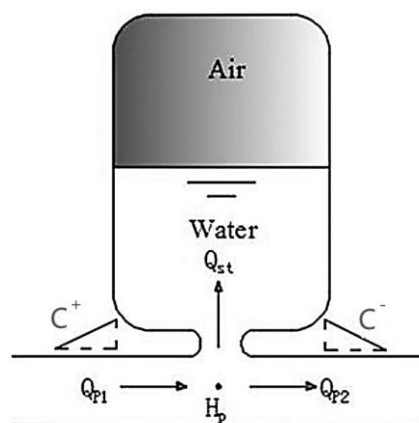


Fig. 3. Mathematical model of pressure vessel
 Note: C^+ and C^- are characteristic lines; H_p is the pressure of air container and pipe connection point, m ; Q is the flow, m^3/s

In 2022, Xiao Xue, Li Legend et al. [34] used the characteristic line method and Latin hypercube sampling method to extract sample parameters by establishing a water hammer model of pipeline transient flow during pump stoppage in long-distance transmission pipelines, and carried out global sensitivity analysis based on partial correlation analysis, and the results showed that the three parameters with higher sensitivity for maximum water strike pressure were pipe diameter, valve closing time and water delivery flow.

4. THE ESTABLISHMENT OF WATER HAMMER MODEL

At present, for the calculation of water hammer pressure in long-distance pipeline most of the water flow as a one-dimensional non-constant flow, and multi-dimensional non-constant flow is often more reflective of water hammer characteristics. For two-dimensional, three-dimensional fluid-structure coupling water hammer theory calculation results are less, but there are more software development in this field, such as: ANSYS-Workbench, FLUENT, MSC.NASTRAN, ADINA, etc. [35], the function of each has a variety of advantages. Commercially available software for water hammer calculations are Flowmaster, Bentley hammer, PIPENET, AFT, etc. [36], most of them are based on the theory of the characteristic line method. The most powerful one is Bentley hammer, which predicts the hazard in advance by building a hydrodynamic model and simulating the occurrence of water hammer, which not only evaluates the risk of water hammer, but also facilitates the development of economical and reasonable water hammer protection measures to minimize the loss of pipelines as much as possible [37].

Yang Yu et al. [38]. on the combination of water hammer mathematical model and boundary condition model, using VC++ language to write the water hammer calculation program, and Bentley Hammer water hammer calculation software to compare the results obtained, confirmed the accuracy of the written program, but also to verify the reliability of Hammer software. Tang Linjun [39] used Bentley hammer to carry out water hammer simulation calculation for a certain section of South-to-North Water Diversion project and a water supply project, and found that adding butterfly valves could reduce water hammer pressure and reverse flow. If the combination of butterfly valve, air valve and pressure regulating well is used, the elevation along the envelope line and the probability of water pump reversal can be greatly reduced. Zhao Juan [40] used Bentley Hammer software to explore the boundary conditions of water hammer and water column separation model for stopping the pump, and carried out hydraulic transition calculations for two cases of whether to set the regulating tower for the pump station system, respectively, to verify the necessity of the regulating tower. The pump after setting the regulating tower, the pressure fluctuation is flat, the fluctuation period becomes longer and the amplitude becomes smaller. The pressure transient at inlet of pump is shown in Fig. 4. Bentley Hammer water hammer calculation software has a powerful target in water hammer calculation, which can accurately simulate the fluctuation process of water hammer, Bentley Hammer combined with finite element software, can derive the stress-strain relationship of the diversion pipeline, which helps Further study of the hazards caused by water hammer has good prospects for the future.

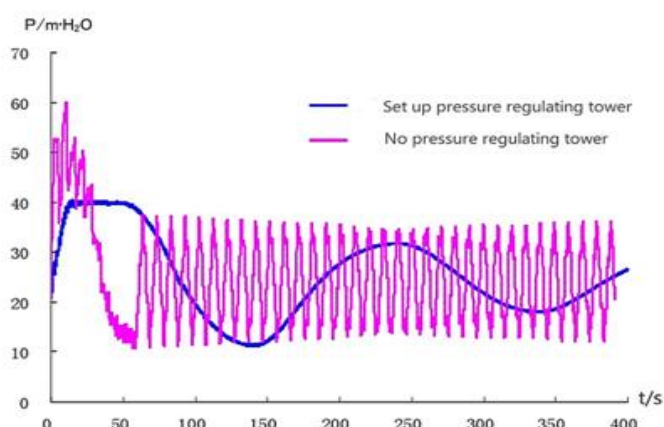


Fig. 4. Pressure transient at inlet of pump

Subsequently, Sun Zhongyuan, Liu Dongfang et al. [41] conducted CFD simulation based on FLUENT software to analyze the flow and heat transfer situation of the accident pipe network in a thermal power plant water hammer burst accident. In addition, CFD simulation of the optimized pipe network is carried out to verify that the distribution of temperature, pressure and velocity at the burst point of the pipe network is more uniform and reasonable. Bentley Hammer water Hammer calculation software is highly targeted in water hammer calculation and can accurately simulate the fluctuation process of water hammer. By combining Bentley Hammer with finite element software or FLUENT software, the stress-strain relationship of water pipeline can be obtained, which is helpful to further study the harm caused by water hammer. The future holds good prospects.

5. CONCLUSION

The occurrence of water hammer effect in the project will lead to serious consequences, ranging from noise and vibration to reduced operation efficiency, to seepage, explosion and equipment damage. At present, although many scholars have conducted a lot of research on water hammer and achieved results in some fields, the water hammer effect is still considered as one of the unsolved problems today. The research on the calculation method of transient flow stroke and the protection of water hammer is not mature yet and there are still some problems to be solved.

- (1) In the calculation of long-distance pipeline water hammer pressure, we generally regard the water flow as a one-dimensional non-constant flow, and multi-dimensional often better reflect the characteristics of water hammer. If the study object is changed from a single liquid to a mutually coupled two-phase or three-phase flow, the applicability of the previous theories and calculation methods remains to be verified.
- (2) The traditional water hammer calculation model are simplified model, although the calculation is simple, but the accuracy is not high. When dealing with complex hydraulic transition process, the calculated value and the actual value is often very different, the value of the actual project is not much. With the continuous development of computers, the ability to accurately analyze the complex hydraulic

transition process will become the object of future research.

- (3) From the point of view of the effect of water hammer, the factors that can have an impact on it are mainly fluid form, valve opening and closing, pipe structure, liquid flow rate, etc. The fluid form, liquid flow rate is difficult to control, researchers are also mainly committed to the study of the use of reasonable valve closing time to reduce the harm caused by water hammer. It is still necessary to adopt reasonable pressure pipeline structure to reduce the harm caused by water hammer.
- (4) There are many kinds of protection measures for water hammer protection of pressure pipeline. Considering the feasibility and economic cost of construction, the combination of several protective measures is selected in the project. For example, the protective effect of the combination of pressure regulating tower, pressure vessel and overpressure relief valve remains to be verified. Although there are many achievements in water hammer protection, accidents caused by water hammer effect often occur in hydropower stations. Therefore, it is still urgent to find an effective and economical protective measure.

Research on these aspects is still the focus of future topics and needs to be further studied and explored by researchers.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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