Review Article

Status of research on water hammer effect in long distance pressure pipelines

ABSTRACT

In long-distance pressure pipelines, the phenomenon of rapid change in liquid flow rate, thus causing drastic changes in instantaneous pressure, is called water hammer, which seriously threatens the safe operation of hydropower plants. This paper introduces the development of transient water hammer theory and the calculation method in detail, and briefly explains the current development trend and problems of water hammer, aiming to urge colleagues to pool their wisdom and open up new research fields.

Comment [n1]: Abstract should be rewritten to summarize the work; the abstract should state briefly the purpose of the research, the principal results and major conclusions.

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

1. INTRODUCTION

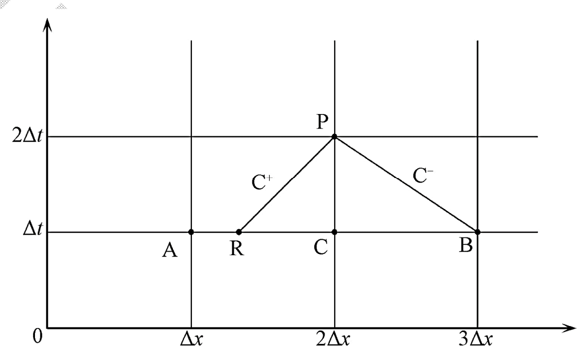
Pressure pipes are an important part of pumped storage power plants, which introduce water from the reservoir forebay into the turbine under pressurized conditions to meet power generation requirements [1]. In recent years, with the increase of hydropower plant scale and the construction of high-head 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 (shown in Figure 1) 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. 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. 1858, Italian engineer Menabrea [3] conducted a study on the phenomenon of water impact, and proposed the theory of elastic water hammer and used the compressibility of fluid and the elasticity of pipe materials to derive the wave velocity calculation formula, which has laid the theoretical foundation of elastic water hammer since then. 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 [7] gave the equation of water hammer pressure about wave speed and flow velocity change.

In 1903, Allievi [8] specified that the convective term in the kinetic energy equation could not be ignored and established the basic differential equation for non-constant flow, and in 1913, he proposed the famous Allievi [9] water hammer chain equation, water hammer diagrammatic curve, and end-phase water strike calculation formula, which made a remarkable contribution to the calculation of indirect water hammer, but because of the limitation that it is only applicable to simple pipelines with negligible friction, the theory was widely used in the early 1930s. In 1926, Wood [10] proposed the graphical method on the basis of his predecessors, which ushered in a new breakthrough in water hammer theory; 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, the characteristic line grid as shown in Figure 2, by the known points R and B, the unknown quantity P point of the head and flow velocity can be found.



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.

Fig.2. Characteristic line method interpolation grid[13]

After the 1960s, with the popularization of computers, Wylie, Streeter and others [14] proposed an electrical algorithm based on the characteristic line method, which greatly improved the accuracy of water hammer calculations; then published hydraulic works "Hydraulic Transient" and "Fluid Transient", from then on water hammer theory entered the computer era. 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 [15] published "Water Hammer in Industrial Pipelines", which solved the common water hammer problems in engineering. 2004, Jin Cone and others [16] wrote "Stop Pump Water Hammer and Its Protection", which explored the water hammer in The problem of water column separation and then bridging. 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 [18], 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. With the popularity of computers, the graphical method gradually retired from the historical stage, and a new field, numerical simulation, was introduced.

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 impact differential equations into a set of difference equations before calculation, 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, can not well simulate the water hammer decay change law and has limitations. The implicit finite difference method has good stability in solving the differential equations and can clearly present the variation law of water hammer, but is too complicated in solving the nonlinear system of equations [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. Then, Liu Zhuxi [23] and others studied the full characteristic curve of the pump and successfully applied the electrocomputing technique and the characteristic line method to the engineering examples of water hammer calculation in hydropower stations, and published the monograph "Water Hammer and Its Protection in Pumping Stations" in 1988. Zhugeqi [24] and others 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. lakis and Selmane [25] applied the Sander thin shell and potential flow theory to study the self-vibration characteristics of pipes. Lisheng Suo [26] and others 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.

Zhang Lixiang and Huang Wenhu [27] 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. 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 [28] 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.

In recent years, Yu Shurong [29] et al. 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 [30] et al. 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.

2022, Xiao Xue, Li Legend et al [32] conducted a global sensitivity analysis based on partial correlation analysis by establishing a water hammer model of pipeline transient flow during pump stoppage in a long distance water pipeline, using the characteristic line method and Latin hypercube sampling method to extract sample parameters, and the results show that : The three parameters with higher sensitivity to the maximum water hammer pressure are pipe diameter, valve closing time and water delivery flow rate.

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. [33], the function of each has a variety of advantages. Commercially available software for water hammer calculations are Flowmaster, Bentley hammer, Pipenet, AFT, etc. [34], 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 [35].

Yang Yu [36] et al. 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 [37] used Bentley hammer to simulate water hammer in a section of south-north water transfer and a water supply project, and found that the water hammer pressure and reversal flow could be reduced by adding butterfly valves; if a combination of butterfly valves, air valves and pressure regulating wells was used, the elevation along the envelope and the probability of pump reversal could be reduced to a great extent. Zhao Juan [38] 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. As can be seen from Figure 3, the pump after setting the regulating tower, the pressure fluctuation is flat, the fluctuation period becomes longer and the amplitude becomes smaller. 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.

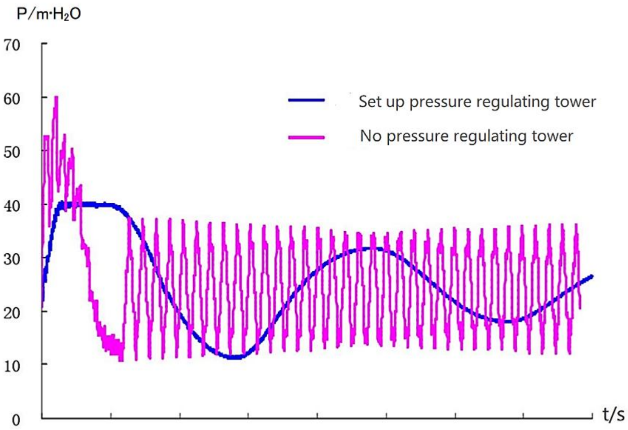


Fig.3. pressure transient at inlet of pump

5 DEVELOPMENT TREND AND PROBLEMS

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 transient water impact calculation methods and water hammer models is not yet mature, 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. Although there are a lot of results about water hammer protection, but hydroelectric power plant accidents due to water hammer effect often occur. Therefore, the search for an effective and economically reasonable protective measure is still a top priority.
Research on these aspects is still the focus of future topics and needs to be further studied and explored by researchers.

REFERENCES

1. Li B J. The hazards of water hammer and emergency disposal measures [J]. Science and Technology Innovation Herald. 2022,19(2) :83-85.
2. Chen Y C. Safety and water hammer hazard protection technology of long-distance pipeline water transmission project [J]. Journal of Drainage and Irrigation Machinery Engineering. 2021(10): 1027-1032.
3. Menabrea L F. Note surles effects de chocdeleaudans les conduits [J]. ComptesRendusHebdomadaires des Seances de L. 1958,47 :221-224.
4. Yang C M, Zhang J S. Apparatus Inducing Water-hammer and the Analysis and Experiment of the Water-hammer Pressure Wave Propagation in the Water System [J]. Fluid Machinery. 2014(09) :10-13.
5. D. A. Gubaidullin, B. A. Snigerev. Numerical Simulations of Subcooled Boiling Flow in Vertical Pipe at High Pressure [J]. Lobachevskii journal of mathematics. 2019,40(6) :745-750.
6. Yu D g, Hu M, Yao R, et al. Handling Method of Unsteady Friction in Water Hammer Evaluation [J]. Design of Hydroelectric Power Station. 2004(02) :3-6.
7. Frizell J P. Pressure Resultiong from Changes of Velocity of water in Pipe [J]. Trans. Amer. Soc. Civil Engrs. 1898,39 :1-18.

8. Zhang J, Li D Z, Jie S P, et al. Pump failure water hammer propagation formula considering friction in long-distance water supply system [J]. Journal of Hydroelectric Engineering. 2015(09) :92-97.
9. Greco M. Computation of energy dissipation in transient flow - Discussion [J]. Journal of hydraulic engineering. 1998,124(5) :559.
10. Zheng M, Chen C, Yuan S Q. Full Characteristic Curve Method for Numerical Calculation of Water Hammer [J]. Transactions of the Chinese Society for Agricultural Machinery. 2000(05) :41-44.
11. Hai, Bhuiyan Shameem Mahmood Ebna Bause, Markus Kuberry, et al. Modeling and simulation of Ultrasonic Guided Waves propagation in the fluid-structure domain by a monolithic approach [J]. Journal of Fluids and Structures, 2019,88 :100-121.
12. Zhao Z, Zhao X F, Wan J X, et al. Research on water hammer protection of long distance pressurized water transmission system based on characteristic line method [J]. Water & Wastewater Engineering. 2019(S1) :277-280.
13. Zhang Q L, Huang B Y, Yang Z D, et al. Water hammer properties of gas-bearing water pipeline using characteristics method [J]. Transactions of the Chinese Society of Agricultural Engineering. 2022(05) :79-86.
14. Streeter V.L. Transient cavitating pipe flow [J]. ASCE Journal of Hydraulic Engineering. 1983,
109(11) :1408-1423.
15. Chen F M. Anatomy of water hammer phenomenon in industrial piping systems [J]. Shanghai Energy Conservation. 2004(06) :22-25.
16. Wen B K. Water Hammer and Its Protection Measures of Industrial Piping Systems [J]. Guangdong Chemical Industry. 2010(04) :199-200.
17. Li S X, Meng L Q, Xu X G, et al. Influence of Opening Characteristics for Ultra-supercritical Steam Trap on Water Hammer Induced Pipe Vibration [J]. Journal of Vibration, Measurement & Diagnosis. 2017(06) :1169-1174+1280.
18. Wang C. Comparative study of theoretical calculation methods for transient flowing water strikes in pressure pipelines [D]. Kunming University of Science and Technology,China,2021.
19. Wang N, Zhou L, Li Y J, et al. Finite volume model of water column separation and bridging water hammer in viscoelastic pipes [J]. Chinese Journal of Theoretical and Applied Mechanics. 2022(07) :1952-1959.
20. Sun Y D, Liu Z Z, Liu J H, et al. Application of MOC to calculation of fluid-structural coupling response of piping system under impact of waterhammer [J]. Journal of Ship Mechanics. 2005(04) :130-137.
21. Liu J. Numerical Investigation of Water Hammer in Pressure Pipes Based on Flow-3D [D]. Harbin Institute of Technology,China,2017.
22. Guo Q, Zhou J X, Huang Y, et al. Water hammer and vibration analysis of a thick-wall pipe considering fluid-structure interaction [J]. Transactions of the Chinese Society of Agricultural Engineering. 2020(21) :137-144.
23. Song Y, Huang Y. Case analysis on pump-stopping water hammer control of pressurized transmission pipelines [J]. Water Technology. 2016(03) :42-45.
24. Zhu G Q, Cai Y G, Yang S C, et al. An Approach to Mathematical Modeling of Piping System With Fluid-Structure Interaction [J]. Journal of Hydrodynamics. 1989(01) :6-12.
25. A.A. Lakis, A. Selmane. Hybrid finite element analysis of large amplitude vibration of orthotropic open and closed cylindrical shells subjected to a flowing fluid [J]. Nuclear engineering and design, 2000,196(1) :1-15.
26. Suo L S, Liu Y M. Form Optimization of Air Cushion Surge Chamber [J]. Journal of Hohai University. 1998(06) :11-15.
27. Zhang L X, Huang W H. Nonlinear Dynamical Modeling of Fluid-Structure Interaction of Fluid-Conveying Pipes [J]. Journal of Hydrodynamics. 2000(01) :116-128.
28. Sun S J, Gao F, Tang X. Programming and application of the characteristic line method in simple pipe water strike calculations [J]. Henan Water Resources & South-to-North Water Diversion. 2007(09) :72+74.
29. Yu S R, Ma L, Yu L. Analysis of Dynamic Characteristics of Fluid-structure Interaction in Curved Infusion Pipelines [J]. Noise and Vibration Control. 2015(04) :43-47.
30. Cao Y P, Huang Y X, Yu K Q, et al. Natural frequency analysis for fluid-solid coupling vibration of completion string based on ANSYS workbench [J]. Well Testing. 2018(01) :1-7.
31. Tan Y. Study of hydroelectric power station pressure pipe fluid-solid coupling water strike and its vibration characteristics [D]. Kunming University of Science and Technology,China,2018.
32. Xiao X, Li C Q, Yang X Z. Analysis on Global Parameter Sensitivity of Fluid Transient Water Hammer Calculation Model [J]. Yellow River. 2020(04) :157-160.
33. Chen Y F, GU W G, WANG D Z, et al. Experimental study and numerical calculation of water hammer effect of closing valve of ball type regulating valve [J]. Journal of Drainage and Irrigation Machinery Engineering. 2021(10) :1027-1032.
34. He Y W. Application of Graphical Method and Hydraulic Simulation Software Modeling Calculation Method in Water Hammer Calculation [J]. Hongshui River. 2022(03) :36-41.
35. Wang Y L, Liu Y C. Bentley Hammer Software for Water Hammer Protection in Pumping Stations [J]. China Water Transport. 2012(09) :86-87.
36. Yang Y. Study on Waterhammer Protection in Long Distance and Large Scale Area of Water Diversion System [D]. Chang'anUniversity,China,2019.
37. Tang L J. Study on Hydraulic Transition Process of Multi Pump Combined Water Conveyance System [D]. North China University of Water Resources and Electric Power,China,2018.

38. Zhao J. Study on the Hydraulic Transition and Protective Measuures of the Water Conveyance System of the Third Stage Pumping Station of Gao Jiata [D]. Xi'an University of Technology,China,2020.