Research and development of visual numerical simulation software for transient process of hydropower station

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Abstract: Transient process is the basis of the safe and stable operation of hydropower station. The calculation of transient process is realized by professional numerical simulation software. This paper presents the research and development of the visual numerical simulation software for transient process of hydropower station. The software is designed and developed based on the Java language and the Eclipse and IntelliJ IDEA development environment. The research and development thought contains five aspects. Firstly, the mathematical model for the transient process of hydropower station is established and the algorithm is adopted. The program for numerical simulation is designed. Secondly, based on the modularization design principle, the object modules and operating condition modules are designed and encapsulated. Thirdly, the user-oriented visual interface of the software is designed and programmed. The visual interface includes menu bar, toolbar and plotting area, which realize the drawing of topology of hydropower station, input of parameters, setting of calculation conditions and post-processing of calculation results. Fourthly, the foreground and background interaction based on graphic interface is achieved to realize the recognition of topology, automatic coding of object modules and transfer of foreground data. Finally, the mathematical model, algorithm, object modules, operating condition modules, visual interface and foreground and background interaction are integrated and the development of the visual numerical simulation software is completed. The visual numerical simulation software for transient process of hydropower station is a general software and has a friendly user interface. Test and application of practical engineering prove the correctness, reliability and precision of the software. The visual numerical simulation software provides a simple, practical and efficient tool for the calculation of transient process of hydropower station.

1. Introduction

Transient process is the basis of the safe and stable operation of hydropower station [1]. The research methods for transient process of hydropower station contain theoretical analysis, numerical simulation and model test. For the engineering applications, the most effective method is numerical simulation. The numerical simulation for transient process of hydropower station is based on the theory of transient flow. The transient flow contains unsteady flow in pressurized pipeline, unsteady flow in open channel and unsteady flow in free surface-pressurized flow tunnel [2]. The important boundary conditions of hydropower station, such as turbine, generator, governor and load, are based on the theories of mechanical engineering, electrical engineering and automatic control. The method of characteristics is the most widely used algorithm for solving the equations of transient flow [3].
The calculation of transient process of hydropower station is a difficult work and needs heavy workload. Therefore, in engineering applications, the calculation of transient process is realized by professional numerical simulation software. But the research and development of visual numerical simulation software for transient process of hydropower station make slow progress. At present, the general visual numerical simulation software for transient process of hydropower station is very limited. For the existing visual numerical simulation software, many weaknesses impede the spread and application [4]. The weaknesses mainly include badly human-computer interaction, less calculation functions, badly pre-processing and post-processing, lack of secondary development function and low calculation stability.

In order to overcome the above weaknesses, the research team of the authors carries out the research and development of visual numerical simulation software for transient process of hydropower station.

2. Design concept and thought

The orientation for the visual numerical simulation software for transient process of hydropower station is a general and standard software. The visual numerical simulation software is user-oriented and has friendly human-computer interaction. The general modeling and calculation for transient process of hydropower station is based on graphics system and visual interface. The visual numerical simulation software should contain the following functions:

(a) Modular modeling of the components of hydropower station.
(b) Arbitrarily call the modules and algorithms.
(c) Interactive visual graphical input of layout and parameters of hydropower station.
(d) Automatic coding and recognition of topological relations of pipeline layout based on graphics system.
(e) Seamless connection and interaction between data and graphs.
(f) View and processing of the calculation results.

Based on the above functions, the overall design and logical framework of the visual numerical simulation software for transient process of hydropower station are shown in Figure 1. The framework of the visual numerical simulation software for transient process of hydropower station has three-tier architecture, i.e. back-end model, middle-tier interaction and front-end interface. The programming and development of the visual numerical simulation software are realized by Java language.

![Figure 1. Overall design and logical framework of the visual numerical simulation software for transient process of hydropower station.](image)
3. Development of three-tier architecture

3.1. Back-end model

The basic equations for unsteady flow in pressurized pipeline contain the continuity equation and momentum equation. When the effects of the elasticity of the water and the pipeline wall are considered, the continuity and momentum equations for unsteady flow in pressurized pipeline are [1,2]

\[
\frac{Q}{A} \frac{\partial H}{\partial t} + \frac{\partial H}{\partial t} + \frac{a^2}{gA} \frac{\partial Q}{\partial t} + \frac{a^2}{gA} \frac{\partial A}{\partial x} - \frac{Q}{A} \sin \theta = 0 \tag{1}
\]

\[
gA^2 \frac{\partial H}{\partial x} + Q \frac{\partial Q}{\partial x} + A \frac{\partial A}{\partial t} + \frac{fQ|Q|}{2D} = 0 \tag{2}
\]

where \( x \) is the distance along the pipeline axis, \( \theta \) is the angle between the pipeline and the horizontal, \( A \) is the cross-sectional area of the pipeline, \( a \) is the wave speed of water hammer, \( H \) is the pressure head, \( Q \) is the flow through the pipeline, \( f \) is the Darcy-Weisbach resistance coefficient, and \( D \) is the diameter of the pipeline. For a non-prism pipeline, \( A \) is a function of \( x \) and we have \( \partial A / \partial x \neq 0 \). For a prismatic pipeline, \( \partial A / \partial x = 0 \).

Equation (1) and equation (2) are quasilinear hyperbolic equations. The method of characteristics is the most widely used method for solving equation (1) and equation (2). By using the method of characteristics, equation (1) and equation (2) can be converted into algebraic equations. It should be noted that the convective terms in equation (1) and equation (2) are considered. The pipeline of hydropower station are divided into many calculation sections. The calculation is carried out from one time step to the next. At any time step, the \( Q \) and \( H \) can be analytically solved.

Besides pipelines, there are many components in hydropower station, including turbine, generator, governor, load, reservoir, surge tank, bifurcation point, valve, pressure regulating valve and gate slot. Those components are regarded as the boundary conditions. The mathematical models for those components are established in many literatures [5,6]. The boundary conditions and basic equations are jointly solved by using the method of characteristics.

The initial conditions are the values of all the parameters of hydropower station when the hydropower station is at the steady flow state.

By combining the basic equations, boundary conditions and initial conditions, the transient processes of hydropower station under any unsteady flow states can be calculated. In practical application, the transient processes of hydropower station are divided into three types, i.e. large fluctuation operating condition, small fluctuation operating condition and hydraulic disturbance operating condition [7]. The large fluctuation operating condition contains start-up, load rejection and shutdown. The small fluctuation operating condition contains load adjustment and frequency adjustment. The hydraulic disturbance operating condition is actually the combination of large fluctuation operating condition and small fluctuation operating condition. For the different operating conditions, the difference of the calculation of transient processes is the settings of the motion law of guide vane. Under a certain operating condition, the motion law of guide vane is known and realized by the governor. Then the whole mathematical model for the transient process of hydropower station is closed and solvable.

3.2. Middle-tier interaction

Middle-tier interaction connects the back-end model and front-end interface. The functions of middle-tier interaction contain the recognition of topological relations of pipeline layout and the data transmission between back-end model and front-end interface. The key technology of middle-tier interaction is the automatic coding of topological relations of pipeline layout based on graphics system. The object-oriented method provides a basis for the implementation of automatic coding. Automatic coding converts the topological relations of pipeline layout based on graphics system into data
description, which can be automatically processed by the computer.

The pipeline system of hydropower station is directed. The flow of water and propagation of water hammer wave have specific directions. Therefore, the numerical calculation should base on a specific direction, such as from upstream reservoir to downstream reservoir. The automatic coding of topological relations of pipeline layout includes the following two functions, i.e. numbering function and line identification function.

(a) Numbering function

Number for every node and establish the incidence relation between one node and its upstream / downstream nodes. For every node, three data members should be added for the numbering. The first data member represents the numbering for the current node. The second data member represents the upstream incidence relation of the node and stores the numbering for the upstream node. The third data member represents the downstream incidence relation of the node and stores the numbering for the downstream node. Moreover, the numbering function is dynamic. When the topological relations of pipeline layout change, the three data members change correspondingly.

(b) Line identification function

Arrange all the nodes and pipes into pipelines based on the direction from upstream reservoir to downstream reservoir. If there is only one pipe on the upstream / downstream side of every node, the arrangement of pipeline is easy to realize. The line identification is started from upstream reservoir to downstream reservoir. Only one pipeline is identified for every time of identification. The line identification is terminated automatically when the downstream reservoir is identified and the unique pipeline is completely hunted. However, bifurcation point often appears in the pipeline layout. For that condition, a method of segmentation coming across bifurcation point is proposed to realize the line identification function. That method is also started from the upstream reservoir. When the line identification comes across a bifurcation point, one line is divided into several lines. For the different bifurcation lines, the line identification continue and is terminated automatically when the downstream reservoir is identified. The procedures for the method of segmentation coming across bifurcation point is shown in Figure 2.

![Figure 2](image-url)

**Figure 2.** Procedures for the method of segmentation coming across bifurcation point.
3.3. Front-end interface

For the visual numerical simulation software for transient process of hydropower station, the design of front-end interface follows the principles of simplicity, clear primary-secondary and friendly human-computer interaction. The main interface of the visual numerical simulation software for transient process of hydropower station is shown in Figure 3.

![Main interface of the visual numerical simulation software for transient process of hydropower station.](image)

The main interface contains three parts, i.e. menu bar, model plotting area and parameter input area. The mathematical modeling, parameter input, operating condition setting, calculation and results processing are realized through the main interface by specific operations. The menu bar includes nine items, i.e. start, modeling, function, characteristic curves of turbine, calculation, results query, report output, local head loss and help. The function introduction of the nine items are shown in Table 1.

| Item               | Function                                                                 |
|--------------------|--------------------------------------------------------------------------|
| Start              | Open or save file.                                                      |
| Modeling           | Establish the model of transient process of hydropower station and input parameters of hydropower station. |
| Function           | Check the established model of transient process of hydropower station.  |
| Characteristic curves of turbine | Extend the characteristic curves of turbine and conduct the Suter transformation. |
| Calculation        | Set the computing time and conduct the calculation of transient process of hydropower station. |
| Results query      | View the calculation results and conduct the results processing.          |
| Report output      | Output report about the calculation results based on required format.     |
| Local head loss    | Calculate the coefficient of local head loss automatically.              |
| Help               | Introduce the functions of software.                                     |
4. Application example

After the development of three-tier architecture, the visual numerical simulation software for transient process of hydropower station can be integrated. Then the visual numerical simulation software can be applied for the numerical simulation for transient process of hydropower station. The application procedures are shown in Figure 4.

![Image of application procedures](image)

**Figure 4.** Application procedures of the visual numerical simulation software for transient process of hydropower station.

In order to illuminate the application effect of the visual numerical simulation software, the transient processes of an actual example are calculated. That example is an actual pumped storage power station in China. There are two hydraulic layout units of the pumped storage power station. For each hydraulic layout unit, one headrace tunnel supplies water for two pumped storage units and a surge tank is set on the headrace tunnel. The rated head, discharge and power output of turbine are 540.0 m, 62.09 m$^3$/s and 306.1 MW, respectively. Based on the actual layout and parameters of the pumped storage power station, the topological relations and model are established by using the visual numerical simulation software and the result is shown in Figure 5.

![Image of topological relations and model](image)

**Figure 5.** Topological relations and model of pumped storage power station established by using the visual numerical simulation software.

Based on the model in Figure 5 and application procedures in Figure 4, four operating conditions of transient process of pumped storage power station are calculated. The introduction about the four operating conditions are shown in Table 2.

| Operating condition | Introduction |
|---------------------|--------------|
| OC-1                | (a) Large fluctuation operating condition (b) Simultaneous load rejection of two pumped storage units from rated power generation operation |
| OC-2                | (a) Large fluctuation operating condition (b) Simultaneous pump power-off of two pumped storage units from rated pumping operation |
| OC-3                | (a) Small fluctuation operating condition (b) Simultaneous load reduction of 5% rated power output of two pumped storage units from rated power generation operation |
| OC-4                | (a) Hydraulic disturbance operating condition (b) Load rejection of one pumped storage unit from rated power generation operation, and rated power generation operation of the other pumped storage unit |

The calculation results for the transient processes under four operating conditions are shown in Figures 6-9.
Figure 6. Calculation results for the transient processes of one pumped storage unit under OC-1.

Figure 7. Calculation results for the transient processes of one pumped storage unit under OC-2.
Figure 8. Calculation results for the transient processes of one pumped storage unit under OC-3.

Figure 9. Calculation results for the transient processes of the rated operation pumped storage unit under OC-4.

The calculation results in Figures 6-9 satisfy the physical laws of transient processes of pumped storage power station. The visual numerical simulation software has also been applied into the calculation for transient process of other hydropower stations and shows excellent convenience, accuracy and stability.

5. Conclusions

(1) The orientation for the visual numerical simulation software for transient process of hydropower station is a general and standard software. The visual numerical simulation software is user-oriented and has friendly human-computer interaction. The general modeling and calculation for transient process of hydropower station is based on graphics system and visual interface.

(2) The framework of the visual numerical simulation software for transient process of hydropower station has three-tier architecture, i.e. back-end model, middle-tier interaction and front-end interface. Back-end model realizes the modular modeling of the components of hydropower station and arbitrarily call the modules and algorithms. Middle-tier interaction connects the back-end model and front-end interface. Middle-tier interaction realizes the recognition of topological relations of pipeline layout and the data transmission between back-end model and front-end interface. Front-end interface realizes the interactive visual graphical input of layout and parameters of hydropower station, start of calculation and processing of the calculation results. The main interface contains three parts, i.e. menu bar, model plotting area and parameter input area.

(3) The calculation results of the visual numerical simulation software satisfy the physical laws of transient processes of pumped storage power station. The visual numerical simulation software has
also been applied into the calculation for transient process of other hydropower stations and shows excellent convenience, accuracy and stability.

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