Vibration analysis of hydropower house based on fluid-structure coupling numerical method

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Abstract: By using the shear stress transport (SST) model to predict the effect of random flow motion in a fluid zone, and using the Newmark method to solve the oscillation equations in a solid zone, a coupling model of the powerhouse and its tube water was developed. The effects of fluid-structure interaction are considered through the kinematic and dynamic conditions applied to the fluid-structure interfaces (FSI). Numerical simulation of turbulent flow through the whole flow passage of the powerhouse and concrete structure vibration analysis in the time domain were carried out with the model. Considering the effect of coupling the turbulence and the powerhouse structure, the time history response of both turbulent flows through the whole flow passage and powerhouse structure vibration were generated. Concrete structure vibration analysis shows that the displacement, velocity, and acceleration of the dynamo floor respond dramatically to pressure fluctuations in the flow passage. Furthermore, the spectrum analysis suggests that pressure fluctuation originating from the static and dynamic disturbances of hydraulic turbine blades in the flow passage is one of the most important vibration sources.

Key words: hydropower house; fluid-structure interaction; Navier-Stokes equations; structural vibration; numerical simulation

1 Introduction

Mechanical vibration sources, electromagnetic vibration sources, and hydraulic vibration sources are generally considered the main causes of hydropower house vibration. The hydraulic vibration source is generally considered the uppermost vibration source. This includes the low frequency vortex rope in the draft tube, the intermediate and high frequency vortex rope, the hydraulic imbalance originating from uneven water seam clearance, and pressure fluctuations caused by pulsating currents in the turbine runner chamber. There are many documents and materials about flow passage turbulence and a lot of research has been conducted. Menter (1994) presented a shear-stress transport model that led to major improvements in the prediction of adverse pressure gradient flows. Yang and Cao (1998) presented a practical \( k-\varepsilon \) two-equation turbulence model to simulate the turbulent flow through a draft tube of the hydraulic turbine, and developed a set of governing equations for the
turbulent flow. Tensor representation of the governing equations in body-fitted curvilinear coordinate systems was derived using Einstein’s expression. Ran et al. (2008) noted that the numerical methods are very important for predicting a head-discharge curve with positive slopes, and better agreement between calculation results and experimental data was achieved using the Spalart-Allmaras turbulence model and mesh strategy for numerical simulation. Based on the Navier-Stokes (N-S) equations and the standard $k-\varepsilon$ turbulence model, Qian et al. (2007) simulated the three-dimensional unsteady multiphase flow in the whole passage of a Francis hydraulic turbine. The pressure pulsation was predicted and compared with experimental data at positions in the draft tube, in front of runner and guide vanes, and at the inlet of the spiral case. Zhang and Zhang (2009) established a three-dimensional finite element model for the #15 hydropower house of the Three Gorges Project (TGP) and performed a nonlinear dynamic analysis of response to pressure fluctuation. So far, there is no effective way to describe the mechanical vibration source, electromagnetic vibration source, and hydraulic vibration source, or to apply the load to the powerhouse and calculate the response of the concrete structure.

Many papers on fluid-structure interactions and related topics have been published in recent years (Zhang and Hisada 2001; Ohayon 2001; Dettmer and Perić 2006; Matthias 2003; Anwer et al. 2009; Mole et al. 2008). At present, comparatively little investigation has been conducted on this kind of fluid-solid coupling problem, which takes the coupling effects of turbulence and the structure into consideration. Therefore, it is necessary to use the fluid-structure coupling numerical method to analyze the response of the powerhouse and turbulence in the flow passage. This has significance to the vibration analysis of the powerhouse structure.

Using a sliding mesh to deal with relative mesh movement and guarantee the continuity of physical variables, a coupling model of the powerhouse concrete structure, hydraulic turbine, and surrounding fluid was established by applying the shear stress transport (SST) model to the Reynolds equation in the fluid zone and using the Newmark method to solve the oscillation equations in the solid zone. The effects of fluid-structure interactions are considered by applying the kinematic and dynamic conditions to fluid-structure interfaces (FSI). Based on the characteristics of the hydropower house, a three-dimensional numerical model has been established.

2 Analytical theory and method

2.1 Basic equations

The motion of a continuous fluid medium is governed by the principles of classical mechanics and thermodynamics. In a fixed Cartesian coordinate frame of reference, they can be expressed in conservative forms for mass and momentum, respectively (Ge and Sotiropoulos 2007):
\[ \nabla \cdot \mathbf{v} = 0 \]  
(1)

\[ \rho_i \frac{\partial \mathbf{v}}{\partial t} + \rho_i \mathbf{v} \cdot \nabla \mathbf{v} - \nabla \cdot \mathbf{\tau}_i = \mathbf{f}_i \]  
(2)

where \( t \) is the time, \( \rho_i \) is the fluid density, \( \mathbf{v} \) is the fluid velocity vector, \( \mathbf{f}_i \) is the body force vector of the fluid medium, \( \mathbf{\tau}_i \) is the fluid stress tensor, and \( \nabla \) is the Hamilton operator. Leschnizer (1995) utilized the SST model to simulate turbulent flow in the passage of a hydropower house.

Linear elastic vibration equations (Attila 2010) for solids can be written as

\[ \mathbf{L}^T \mathbf{\tau}_s + \rho_s \mathbf{f}_s = \rho_s \mathbf{\ddot{u}} \]  
(3)

where \( \mathbf{\tau}_s \) is the solid stress tensor, \( \mathbf{f}_s \) is the solid body force, \( \mathbf{\ddot{u}} \) is the particle acceleration vector in the solid zone, \( \rho_s \) is the solid density, and \( \mathbf{L}^T \) is the differential operator, which can be expressed as

\[ \mathbf{L}^T = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial z} \\ 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial x} & \frac{\partial}{\partial z} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix} \]

### 2.2 Kinematic and dynamic conditions at FSI

The fundamental conditions applied to the FSI (Treyssede and Ben Tahar 2008; Van Vosse et al. 2003) are the kinematic condition (or displacement compatibility),

\[ \mathbf{d}_j = \mathbf{d}_s \]  
(4)

and the dynamic condition (or traction equilibrium),

\[ \mathbf{n} \cdot \mathbf{\tau}_j = \mathbf{n} \cdot \mathbf{\tau}_s \]  
(5)

where \( \mathbf{d}_j \) and \( \mathbf{d}_s \) are, respectively, the fluid and solid displacements; \( \mathbf{\tau}_j \) and \( \mathbf{\tau}_s \) are, respectively, the fluid and solid stresses (Shangguan and Lu 2004; Chen and Su 2009); and \( \mathbf{n} \) is the unit normal vector. The underlining denotes that the variables are defined on the FSI only. The fluid velocity condition results from the kinematic condition if a no-slip condition is applied:

\[ \mathbf{v} = \mathbf{d} \]  
(6)

Otherwise, if a slip condition is applied:

\[ \mathbf{n} \cdot \mathbf{v} = \mathbf{n} \cdot \mathbf{d} \]  
(7)

The fluid and solid models are coupled as follows: The fluid nodal positions on the FSI are determined by the kinematic conditions. The displacements of the other fluid nodes are determined automatically by the program to preserve the initial mesh quality (Chen and Su 2009). The governing equations of fluid flow in arbitrary Lagrangian-Eulerian formulations are then solved. In steady-state analyses, the mesh velocities are always set to zero even when the fluid nodal displacements are updated. Accordingly, the fluid velocities at the FSI are zero.
According to the dynamic conditions, on the other hand, the fluid traction is integrated into fluid force along the FSI and exerted onto the structure node (Chen and Su 2009):

\[ F(t) = \int h_\delta \tau_{\xi} \cdot dS \]  

(8)

where \( h_\delta \) is the virtual quantity of the solid displacement, \( F(t) \) is the fluid stress vector at the FSI, and \( dS \) is the increment of area of the FSI.

For full Reynolds time-averaged N-S equations, the standard SIMPLE algorithm is used in pressure-velocity coupling. The fluid governing equation is discretized based on the finite volume method, the second-order upwind discretization scheme is adopted for the convection term, and the Newmark method is used for the solution of vibration equations.

### 2.3 Computational conditions and finite element model

A hydropower house in China was used as an example in this study. The hydropower house is 176.76 m long, 54.70 m wide, and 63.90 m high. The turbine installation elevation for the hydropower station is 1299.15 m, the main equipment room elevation is 1276.15 m, the erecting bay elevation is 1312.40 m, and the base for the house is constructed on the bedrock. The hydropower house profile is shown in Fig. 1.

The concrete structure and turbine of the powerhouse and the turbulence were modeled. The meshes are shown in Fig. 2. The concrete structure includes a draft tube, a dynamo floor, and a turbine floor. The concrete structure was divided into 43,996 elements. The flow passage is composed of a spiral case, a stay vane, and guide vanes. Turbulence in the flow passage was divided into 300,928 fluid elements. The powerhouse structures close to the bedrock were fixed in this model. Concrete and steel were the main materials in the calculation process and their parameters are shown in Table 1. The rotational speed of the hydraulic turbine was 100 r/min, the rotation frequency was \( f_n = 1.67 \text{ Hz} \), the velocity in the spiral case inlet was 6.40 m/s, the time step was set at 0.002 s, and there were 3000 steps in the calculation.

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**Fig. 1** Profile of hydropower house (Unit: m)

**Fig. 2** Mesh of hydropower house
The sliding mesh boundary condition was employed to allow meshes in different fluid regions to move relative to each other while the physical variables across the sliding interface remained continuous. The fluid-solid coupling effect was taken into account through the kinematic condition and the dynamic condition at the FSI.

### 3 Analysis of turbulence velocity and pressure

Fig. 3 and Fig. 4 show the velocity vector and pressure distribution of fluid in the flow passage at 4.80 s. The flow velocity is relatively high at the inlet of the hydraulic turbine, and the velocity decreases gradually through the hydraulic turbine runner. The fluid pressure is very high in the volute and decreases gradually in the direction of flow. The water moves through the hydraulic turbine runner and enters the draft tube. There is negative pressure in the draft tube. Part of the fluid kinetic energy is recovered by the draft tube.

![Fig. 3 Velocity vector of fluid in flow passage at t = 4.80 s](image)

![Fig. 4 Pressure distribution of fluid in flow passage at t = 4.80 s](image)

The time history of fluid pressure and its spectrum analysis at the stay ring are shown in Fig. 5. The main frequency of fluid pressure included a low frequency of 0.42 Hz, an
intermediate frequency of 20.02 Hz, and a high frequency of 40.03 Hz. Analysis shows that the low frequency of 0.42 Hz was equal to the frequency of the vortex rope in the draft tube, the influence of the vortex rope was relatively weak, and the amplitude of pressure was only 1734 Pa. The intermediate frequency of 20.02 Hz was 12 times higher than the rotational frequency of the hydraulic turbine, and equal to the frequency of the hydraulic turbine blade. Likewise, the high frequency of 40.03 Hz was 24 times higher than the rotational frequency of the hydraulic turbine. It was equal to the rotational frequency of a guide blade.

Fig. 5 Time history of fluid pressure and its spectrum analysis at stay ring

4 Vibration analysis of powerhouse structure

The vibrations of the dynamo floor were studied. Fig. 6 shows the band plot of displacement extreme, velocity extreme, and acceleration extreme of the dynamo floor, as well as the dynamo floor’s detection points. From the band plot we see that the maximum responses all occur on the dynamo floor. The maximum displacement was 0.008 mm, which is less than the regulation specification of 0.200 mm. The maximum velocity was 2.71 mm/s, which is less than the regulation specification of 5.00 mm/s. The maximum acceleration was 0.62 m/s², which is less than the regulation specification of 1.00 m/s². It can be concluded that the vibration met corresponding specifications and hydraulic vibration did not cause serious damage.

In order to understand vibration response in the time domain and analyze spectrum characteristics and influences of the vibration sources, Figs. 7 through 9 show the displacement, velocity, and acceleration curves at detection point 4 in the time domain and their spectrum analysis. The main frequency of the displacement spectrum analysis at detection point 4 (Fig. 7) included an intermediate frequency of 20.02 Hz with an amplitude of 0.003 mm, which is equal to the rotational frequency of the hydraulic turbine blade, and a high frequency of 40.03 Hz with an amplitude 0.007 mm, which is equal to the rotational frequency of the guide blade. Thus, the floor vibration is mainly caused by static and dynamic disturbances of the hydraulic turbine blade.
The main frequency of the velocity spectrum analysis at detection point 4 (Fig. 8) included a frequency of 80.00 Hz with an amplitude of 0.70 mm/s, which is equal to 48 times the rotational frequency of the hydraulic turbine, and a frequency of 60.00 Hz with an amplitude of 0.27 mm/s, which is equal to 36 times the rotational frequency of the hydraulic turbine. Thus, the floor velocity vibration is mainly caused by frequency doubling of the pressure fluctuations in the turbine runner, and the dynamic and static disturbances of the hydraulic turbine are the main source of vibration.

The time history of acceleration and its spectrum analysis at detection point 4 are shown in Fig. 9. The acceleration amplitude at the frequency of 80.00 Hz, 48 times the rotational frequency of the hydraulic turbine, was relatively large, reaching 0.18 m/s². In comparison
with the acceleration amplitude at 80.00 Hz, the other acceleration amplitudes were smaller and distributed more widely. The analysis demonstrates that the acceleration response is the same as the velocity response, and both are caused by frequency doubling of pressure fluctuations in the turbine runner. The response of acceleration is distributed more widely than the velocity response. For certain calculation conditions, the low-frequency vortex rope does not have a dramatic influence on the vibration, so this study does not analyze this influence in detail. The model also does not consider the vibration energy pathway due to its excessive computation requirement.

5 Conclusions

According to the characteristics of the hydropower house, a three-dimensional numerical model has been established. Numerical simulation of turbulent flow through the whole flow passage of the hydropower station and concrete structure vibration analysis in the time domain were carried out with the model. Some conclusions are drawn as follows:

(1) Considering the effect of coupling the turbulence and the powerhouse structure, the time history response of both turbulent flow through the whole flow passage and powerhouse structure vibration were determined. This is a new attempt at vibration analysis of the
(2) Analysis shows that the maximum responses all occurred on the dynamo floor, and that the vibrations met corresponding specifications for hydraulic vibration and did not cause serious damage.

(3) It is proven with the spectrum analysis that floor vibration is mainly caused by static and dynamic disturbances of the hydraulic turbine blade.

References


