Research on coupling vibration of hydropower house

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Abstract. In order to describe and express the hydraulic vibration source as the exciting force in the vibration analysis of hydropower house, a new coupling method for vibration analysis of house structure-flow passage turbulence is proposed in this paper, and then, the finite element coupling model of Xiangjiaba house is developed. Based on the turbulent field and house structure vibration calculated in the time domain, the coupling vibration relationship between hydraulic vibration source and hydropower house is studied. Fluid pressure fluctuations are mainly caused by low frequency vortex in taper pipe of draft tube and Rotor/Stator interaction; both the low frequency vibration displacements on generator floor which are at primary frequency of 0.625 Hz and 1.25 Hz and the low frequency vibration velocities on generator floor which are at primary of 0.626 Hz and 9.375 Hz are caused by low frequency vortex in draft tube. The results show that the coupling method and corresponding finite element model initiated in this paper succeed in solving the description and expression of hydraulic vibration source. Due to short calculation time and inadequate setting of fluid initial condition, the distributions of maximum vibration value need further research.

1. Introduction
The vibration study of hydropower house mainly relies on prototype observation and numerical simulation. Time domain analysis method is used to solve the vibration response of hydropower house structure and unit in time domain by numerical approach[1-6]. Differences between research productions are mainly manifested as different processing method for excitation load. We take hydraulic vibration source as example. Based on pressure fluctuation obtained by prototype observation or model test in limited positions, interpolations are used to get the hydraulic loads on the surface of flow passage. Due to violent turbulence, it is difficult to estimate the error. In view of the development of Computational Fluid Dynamics (CFD), a new coupling method for vibration analysis of house structure-flow passage turbulence is proposed in this paper, then, the finite element coupling model of Xiangjiaba house structure is developed. Thus, structure vibration of Hydropower house is studied in a new way.

2. House-turbulence coupling vibration analysis method
Based on the two-way coupling iterative solution method, the sliding mesh technology and arbitrary Lagrangian-Eulerian (ALE) method are combined to propose the house-turbulence coupling vibration
analysis method, and the vibration quantity of power plant structure and turbulent flow field in channel are solved.

2.1 Fluid-structure iterative computing method of two-way coupling

The incompressible Navier-Stokes equations are considered to be the governing equations and its weak forms are established using the Galerkin method; governing equations for solid are the structural dynamic equilibrium equations and employ the virtual displacement principle. Finite element equations for fluid and structure are established in frame of finite element method, so the finite element equations of the coupled fluid-structure system can be expressed as

\[
F[X] = \begin{bmatrix}
F_f(X_f, d_f(X_f)) \\
F_s(X_s, \tau_f(X_f))
\end{bmatrix} = 0
\]

where, \(F_f\) and \(F_s\) are finite element equations corresponding to fluid and solid respectively. Iterative computing of two-way coupling method is also called the partitioned method. The fluid and solid solution variables are fully coupled in the solution. The fluid equations and the solid equations are solved individually in succession and the computational procedure can be summarized as follows.

We start with the initial solution guess \(\mathbf{d}_s^0 = \mathbf{d}_s^1 = \mathbf{d}_s^2 = \cdots = \mathbf{d}_s^k\) and \(\mathbf{\tau}_f^0 = \mathbf{\tau}_f^1 = \cdots = \mathbf{\tau}_f^k\). For iterations \(k = 1, 2, \ldots\), the following equilibrium iteration is performed to obtain the solution \(X^{k+1}\).

\begin{enumerate}
  \item Solve the fluid solution vector \(\mathbf{X}_f^k\) from the fluid equation:
  \[
  F_f[\mathbf{X}_f^k, \lambda_d \mathbf{d}_s^{k-1} + (1 - \lambda_d) \mathbf{d}_s^k] = 0
  \]
  \(k = 1, 2, \ldots\)

  \item If only the stress criterion needs to be satisfied, the stress residual is computed and checked against the tolerance. If the criterion is satisfied, steps 3 to 5 are skipped.

  \item Solve the fluid solution vector \(\mathbf{X}_f^k\) from the fluid equation:
  \[
  F_f[\mathbf{X}_f^k, \lambda_d \mathbf{\tau}_f^{k-1} + (1 - \lambda_d) \mathbf{\tau}_f^k] = 0
  \]

  \item The fluid nodal displacements are computed with the prescribed boundary conditions
  \[
  \mathbf{d}_f^k = \lambda_d \mathbf{d}_s^k + (1 - \lambda_d) \mathbf{d}_s^{k-1}
  \]

  \item If only the displacement criterion needs to be satisfied, the displacement residual is computed and checked against the tolerance. If both the stress and the displacement criteria need to be passed, both convergence conditions are checked. If the iteration has not converged yet, the program goes back to step 1 and continues for the next iteration unless a maximum number of FSI iterations have been reached;

  \item Save the fluid and solid solutions.

\end{enumerate}

The iterative method requires less memory than the direct method in two-way couplings. It is more effective for large problems.

2.2 Sliding mesh

The fluid meshes in turbine runner rotate with runner. Flux transfer and momentum conservation are achieved between rotating mesh in runner and static mesh around runner. The sliding mesh technology is designed to allow meshes in different regions to move relative to each other, while the physical variables across the sliding interface remain continuous. The nodal points M, M1 and M2 are sitting at different sides of the sliding mesh interface. The control volume of M is composed of upper and lower sub-volumes. In order to calculate the flux/force over the control volume represented by the node M, we need to deal with upper and lower sub-volumes respectively. For the lower half, there is no
difficulty to get the flux using the information from node M. Meanwhile, the flux for the upper half control volume is calculated using the neighboring nodes M1 and M2, as shown in Figure 1.

![Figure 1. Sliding mesh interface coupling](image)

2.3 Arbitrary Lagrangian-Eulerian (ALE) formulation

Boundary change of the fluid domain is caused by guide vane opening of hydraulic turbine and the problem cannot be overcome by using Eulerian formulation. ALE formulation is introduced into coupling method to deal with mesh adjusting caused by change of the fluid-solid interface.

Let \( \mathbf{v} \) be the fluid velocity and \( \mathbf{v}^\ast \) be the velocity of a reference domain, then the time derivatives in the continuity and momentum equations are obtained by considering an arbitrary volume of the reference domain. For example, the continuity equation is

\[
\frac{\partial}{\partial t} \int_V \rho \mathbf{v} \, dV + \int_S (\rho \mathbf{v}^\ast - \mathbf{v}) \cdot \mathbf{n} \, dS = 0
\]

(5)

\( S \) is the surface of \( V \) and \( \mathbf{n} \) is the unit normal vector. In practice, the velocity of the reference domain is the velocity of the finite element mesh. Special algorithms based on the solution of Laplace equations can be used to calculate the new nodal point positions in fluid mesh.

Time integration for both fluid and solid equations must be consistent due to iterative computing of two-way coupling, so the consistent time integration is employed. Shear Stress Transport model is used to take into account the turbulence effect. Integrating sliding mesh and ALE formulation, hydropower house structure-turbulence coupling vibration analysis method is proposed on the basis of iterative computing method of two-way coupling.

2.4 Numerical model

According to actual size and material properties of Xiangjiaba hydropower house, the finite element coupling model includes house concrete structures and unit and turbulence in the fluid passage, as shown in Figure 2. Furthermore, the responses of fluid and structure are calculated under normal operating conditions in time domain.

Synchronous rotation speed of Xiangjiaba hydropower unit is 75 r/min, that is, \( f_n = 1.25 \) Hz. Time step size is set to 0.002 s and total time steps 4000 in the finite element model.

![Figure 2. the finite element coupling model of Xiangjiaba house](image)
3. Analysis of unsteady flow in whole passage

According to calculations, pressure fluctuation characteristics of unsteady flow are studied. Pressure contours in whole passage is shown in Figure 3.

![Pressure contours in whole passage](image)

**Figure 3. Pressure contours in whole passage.**

| Amplitude (Pa) | Inlet section of volute | Runner inlet | Back of runner blade | Taper pipe of draft tube | Elbow pipe of draft tube | Divergent pipe of draft tube |
|----------------|-------------------------|--------------|----------------------|-------------------------|-------------------------|-----------------------------|
| Frequency (Hz) | 0.626 | 1.25 | 18.77 | 56.32 | 93.87 | 131.41 |
| 2156 | 515 | 410 | 353 | 268 | 898 |
| 3265 | 2283 | **10668** | **1317** | 343 | 459 |
| 3958 | 4659 | 604 | 636 | 142 | 358 |
| 10298 | *5228* | 782 | 631 | 296 | 404 |
| 3245 | 1003 | 225 | 146 | 71 | 74 |
| 215 | 31 | 39 | 12 | 3 | 2 |

Table 1. Primary frequency and amplitude of whole passage flow.

The primary frequency and amplitude of whole passage flow are shown in Table 1. Under normal operating conditions, pressure fluctuations in passage can be divided into two classes, low frequency vortex at primary frequency of 0.626 Hz and 1.25 Hz and middle frequency fluctuations at primary frequency of 18.77 Hz and 56.32 Hz and 93.87 Hz and 131.41 Hz.

The amplitude of low frequency vortex reaches the highest level in taper pipe of draft tube and decreases along upstream and downstream, so it is concluded that this is low frequency vortex happened in draft tube. In the same way, the amplitude of middle frequency fluctuations reaches the highest level in front of runner and decreases along downstream. Furthermore, its frequency value divided by the product of blade number and speed frequency are odd numbers. It is clear that the middle frequency fluctuations are caused by rotor/Stator interaction.

4. Vibration analysis of hydropower house

In order to investigate the internal vibration condition, Maximum vibration value contours and profiles of hydropower house are shown in Figure 4. The vibration time history and corresponding frequency spectrum analysis of the generator floor are shown in Figure 5.

The vibration analysis of hydropower house is discussed in detail.
Combining with maximum vibration value contours and time history of vibration on the generator floor and spectrum analysis, some conclusions are gotten:

- both the low frequency vibration displacements on generator floor which are at primary frequency of 0.625 Hz and 1.25 Hz and the low frequency vibration velocities on generator floor which are at primary of 0.626 Hz and 9.375 Hz are caused by low frequency vortex in draft tube;
- both the middle frequency vibration displacements which are at primary frequency of 18.77Hz and 56.25 Hz and middle frequency vibration velocities on generator floor which are at primary frequency of 37.5 Hz and 75.0 Hz and 112.5 Hz are caused by Rotor/Stator interaction;
- the degree of vibration displacement and velocity and acceleration is not high, and the calculation results comply with the relevant regulations under normal operating conditions.
5. Conclusions
Under normal operating condition, based on the finite element coupling model of Xiangjiaba house, unsteady flow field in the whole passage and the time history vibration of house structure are calculated. Furthermore, the coupling vibration relationships between turbulence in passage and house structure are studied. Some conclusions are gotten for normal operating condition:

- fluid pressure fluctuations are mainly caused by low frequency vortex in taper pipe of draft tube and Rotor/Stator interaction;
- the vibrations on the generator floor are mainly caused by low frequency vortex and Rotor/Stator interaction;
- the hydropower house structure-turbulence coupling vibration analysis method proposed in this paper succeeds in solving the description and expression of hydraulic vibration source.

Due to short calculation time and inadequate setting of fluid initial condition, the distributions of maximum vibration value need further research.

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