Dynamic response analysis of powerhouse under turbine pressure pulsation with different distributions and application methods

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Abstract. Hydraulic excitation oriented from the turbine is one of the main sources of vibration for hydropower plants. Under different operation conditions, the amplitude, frequency and phase of pressure pulsation are different. The pressure pulsation of spiral case belongs to non-stationary waves, including traveling waves and standing waves. In this paper the pressure pulsation distribution characteristics of the spiral case were discussed and two kinds of distributions were assumed. The dynamic response of the powerhouse structure was simulated with FEM model through harmonic response analysis and transient dynamic analysis and the sensitivity of the pressure behaviour on the structure’s response were presented. The time history responses were also calculated under different turbine loads with different amplitude and frequency. The conclusion is that the structure dynamic responses under the traveling or standing waves are all greater than that with uniform assumption. So the distribution characteristics of pressure pulsation should be reasonably simulated to the dynamic analysis of the concrete structure.

1. Introduction
As the greater of the capacity of hydroelectric unit and its eater head, the vibration of the unit shaft system and its supporting systems becomes more serious. There exist mechanical, electrical and hydraulic excitations but the hydraulic excitation originated from the transient flow fields is the critical one. The induced vibration of the powerhouse concrete structure is also need to be evaluated and controlled [1, 2]. The key point for the dynamic analysis of the unit and powerhouse coupling system is how to determine the hydraulic fluctuations in the spiral case, turbine chamber and draft tube. The prototype experiment may be the best method [3, 4], but it is also very difficult to obtain the distribution of the water pressure as the numbers of the pressure transducers being very limited. The situation is also same for the model experiment as the gauging points is generally not more than 10 [5-7]. Based on the CFD analysis [8, 9], the overall characteristics of the pressure fluctuations in normal and transient conditions could be presented, but there also exist uncertainty for the strong unsteady and vortex flows [10-12]. There have also some researches using fluid-structure coupling analysis to solve the hydraulic pressure induced powerhouse vibration [13, 14], which precision is based on the promise of the CFD results.

Generally there exist mainly three types of pressure modes, namely uniform, traveling wave and standing wave. It could be concluded that in the design stage and even in the operation conditions there exist huge difficulty for the determining of the pressure pulsation distributions. So in the conditions of limiting data base from model or prototype experiment, there exists obvious significance to find a convenient and acceptable method to describe the dynamic distribution characteristics of the hydraulic pressure fluctuation of the turbine flow fields, which is the main object of this paper.

2. Simulation of the pressure pulsation
In the stage of project design, the dynamic pressure acted on the flow paths of the water turbine are mainly decided by the experiment of the model turbine. It is assumed generally that the relative value of the pressure pulsation amplitude being same for the model and real turbine. So the pressure peak value could be calculated with following formula,

\[ P = \gamma \Delta H_p = \gamma \frac{\Delta H_m}{H_m} H_p \]  

(1)

For the pressure distribution along the inner wall of spiral case in the main flow direction, there may exist three distribution modes, as shown in figure 1, named uniform, traveling wave and standing wave. For the uniform distribution, it is assumed that along the inner wall the pressure amplitude and frequency is same and there are no phase angle just as in resonance mode.

As for the traveling wave, it is assumed that there has a single wave length along the flow path in this paper. Based on the practical situations, the wave length may be 1/2 or 1/3 of the spiral case flow path. The phase angle is the location angle of the spiral case and the pressure amplitude value is same. So in the harmonic simulation the real and imaginary part of the dynamic load could be expressed as follows,

\[
\begin{align*}
F_{\text{real}} &= P \cos \phi \\
F_{\text{imag}} &= P \sin \phi
\end{align*}
\]  

(2)

Standing wave is the superimposition of two waves in opposite propagating direction with same amplitude. Pressure pulsation could be looked as a kind of standing wave. Here it is assumed that there is only one wave length along the spiral case flow path as shown in figure 2. The pressure pulsation could be expressed as follows,

\[ y = 2A \cos \frac{2\pi}{\lambda} x + \Phi \cos (\omega t + \Psi) \]  

(3)

Where A is wave’s amplitude; \( \lambda \) is the wavelength, same as the flow path length; \( \omega \) is the frequency; \( \phi \) and \( \psi \) are the phase angle of the two waves with opposite directions.

Figure 1. Three different pressure fluctuation wave modes along the spiral case

Figure 2. Distribution mode of standing wave

3. Numerical simulation model and the experiment data
A powerhouse structure is taken as a calculation example, with unit capacity of 200MW, and the turbine head is 57.0m, rated speed is 93.75r/min, named Fengman Power Station located in the northeast of China. The FEM models of the powerhouse and spiral case were shown in figure 3.

![Figure 3. FEM model of the powerhouse and spiral case model](image)

The pressure excitation data is come from the turbine experiment, with three water heads of 44m, 57m and 77m, and the output is from 10% to 100%. For a typical operation condition of 71m (water head) and 45% output, the pressure wave in the inlet of spiral case and frequency spectrum are shown in figure 4.

![Figure 4. Pressure wave and frequency spectrum](image)

The pressure distribution along the flow path is all assumed to be uniform and the dynamic response of the concrete wall of upstream side is shown in figure 5. It is seen that the acceleration response is decreased with the output’s increase. The maximum response of the powerhouse is in the limitation of the standards.

![Figure 5. Acceleration \textit{rms} value in different output](image)

(a) H=71m  (b) H=57m  (c) H=44m

### 4. Dynamic response under different pressure modes

Take the pressure experiment data shown in figure 4 as the dynamic loads acted on the spiral case, processed with three modes shown in figure 1. The pressure peak value is 7379.84 Pa and the main frequency is 0.73Hz, belong to the low-frequency vortex originated from the draft tube. The dynamic response is calculated with harmonic method and the frequency region is taken as 0 ~ 3.1Hz with the total time steps of 30.

Shown in figure 6 are the dynamic responses of generator floor slab in three directions. It could be concluded that under the uniform pressure distribution the vertical displacement is larger than that of the horizontal directions, but for the traveling and standing waves the displacement in longitudinal direction is dominant.

Figure 7 represent the dynamic response of the column in the turbine floor level. It is seen that the maximum displacement is also in the longitudinal direction, especially for the standing wave excitation.
In order to study the response distribution characteristics, some typical node points are marked in figure 8 along the outer edge of the spiral case concrete structure in horizontal section. $\phi_1$ is the inlet of the spiral case. The displacements of this typical nodes at same time step is presented in figure 9.

![Figure 8. Typical nodes along the spiral case outer edge](image)

![Figure 9. Displacement distribution along the outer side of the spiral case](image)

The dynamic response under hydraulic excitations display a different distribution along the outer edge of spiral case concrete structure for the traveling and standing waves. It could be concluded that under the traveling wave there exist obvious phase angle along the flow direction which may be same as that of the pressure pulsation. As for the pressure pulsation with standing wave mode the dynamic responses at any locations are in the same phase position, just as in resonance status.

For the transient response analysis, the vibration trajectory of the inner circle of the spiral case concrete structure are described for the two revolutions in figure 10 and figure 11 for the two wave modes respectively. It is seen that for the traveling wave’s excitation the structure is vibrated in

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(a) longitudinal direction    (b) crossrange direction   (c) vertical direction

**Figure 6.** The dynamic response of the generator floor slab

**Figure 7.** The dynamic response of the column in turbine floor level

**Figure 8.** The dynamic response of the generator floor slab

**Figure 9.** The dynamic response of the column in turbine floor level

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For the transient response analysis, the vibration trajectory of the inner circle of the spiral case concrete structure are described for the two revolutions in figure 10 and figure 11 for the two wave modes respectively. It is seen that for the traveling wave’s excitation the structure is vibrated in
spinning mode with the pressure propagating. As for the standing wave’s excitation the structure is vacillated to the left and right.

![Figure 10. Forced vibration mode of the concrete structure around spiral case (traveling wave)](image1)

![Figure 11. Forced vibration mode of the concrete structure around spiral case (standing wave)](image2)

The maximum value of the vibration speed and acceleration of the slab and column is listed in table 1. It is seen that the response under the traveling wave mode is larger than that under the standing wave, and for uniform pressure distribution the response is the minimum. If the vibration limitation is taken as 5 mm/s and 1.0 m/s² for the powerhouse structure, the vibration level under hydraulic excitations for the example project could meet the requirement.

| Location               | Direction | Uniform wave | Traveling wave | Standing wave |
|------------------------|-----------|--------------|----------------|---------------|
|                        |           | v (mms⁻¹)    | a (mms⁻²)      | v (mms⁻¹)    | a (mms⁻²)      |
| Generator floor slab   | horizontal| 0.065        | 2.087          | 0.211        | 7.753          | 0.102        | 4.925          |
|                        | vertical  | 0.055        | 3.796          | 0.208        | 17.672         | 0.085        | 10.299         |
| Column in turbine floor| horizontal| 0.043        | 2.726          | 0.140        | 7.825          | 0.085        | 6.100          |
|                        | vertical  | 0.020        | 1.795          | 0.055        | 3.382          | 0.037        | 2.484          |

5. Conclusions
In the case of limiting data from turbine model experiment of dynamic pressure pulsations, it is convenient to assume a pressure distribution along the flow path with some kinds of wave modes. From the numerical simulation of this paper it could be concluded that the travelling wave modes for the pressure pulsation in the spiral case is the most unfavourable mode. So when we did not know the exact pressure distribution the travelling wave is a favourable selection.

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