Reinforcement and resonance control of head cover of Francis turbine by finite element analysis and modal testing

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Abstract. This article discusses the problem of excessive vertical vibration of head cover for Francis turbine installed in Baishi hydropower plant, including its treatment and effectiveness evaluation. In order to build the head cover model accurately, to successfully predict the natural frequencies of the head cover after reinforcement, and to control the resonance risk caused by the close proximity between the natural frequency of the head cover and the water pressure pulsation in the flow passage, the method of combining numerical simulation and experimental measurements is carried out. The results show that the natural frequencies of the reinforced head cover avoid main excitation frequencies of the Francis turbine, and the vertical vibration of the head cover is significantly reduced, with a maximum reduction of 73.6%.

1. Introduction

The head cover is not only the hydraulic turbine’s flow passage and the pressure boundary component, but also the crucial structural support as well as the component to transfer load[1]. Its stiffness strength and reliability will affect the safety and stability of the whole hydropower unit. In recent years, with the increase of the size of hydropower units, the stiffness of unit components is relatively weakened and the natural frequency is reduced, the resonance problem of hydraulic turbine has attracted much attention[2-3].

Since the hydropower units were put into operation in Baishi hydropower plant in April 2013, the vertical vibration of all three hydraulic turbine head covers had exceeded the national standard limit, reaching a maximum of 170 μm (national standard limit of 110 μm). In order to ensure the safe operation of the units, the power plant had to adopt the operation mode of vibration avoidance. However, due to the wide power load range of the excessive vertical vibration, the adjustable power load range was narrow, which seriously affected the dispatching of the power plant. Structural modifications were done by welding and plugging the apertures of stiffened plate in order to decrease and control the vibration level. This reinforcement scheme will cause the natural frequencies variation of the head cover, and may lead to the close proximity between the natural frequency of the head cover and the water pressure pulsation in the flow passage which induce resonance. Consequently, it is necessary to estimate the natural frequencies of the reinforced head cover accurately.

In this research, we combine the benefits of both finite element analysis (FEA) and modal testing for structural modification and resonance control of the head cover. Modal testing is a useful tool for verifying and helping improve the accuracy of FEA models of a structure[4]. The equations of motion solved by a FEA are based on an idealized model and are used to predict and simulate dynamic
performance of the structure. They also allow the designer to examine the effects of changes in the mass, stiffness and damping properties of the structure in greater detail\[5\]. For anything except the simplest structures, modeling is a formidable task. Experimental measurements on the actual hardware result in a physical check of the accuracy of the mathematical model. If the model predicts the same modes of vibration that are actually measured, it is reasonable to extend the use of the model for simulation, thus reducing the expense of building hardware and testing each different configuration.

2. FEA and modal testing before structural modification

2.1. Model description

FEA calculation was performed by ANSYS software. The three-dimensional model of the head cover was established according to the geometric characteristics of the design drawing, and the tetrahedral mesh element with middle nodes was adopted to generate mesh, with a total of 649,239 nodes and 290,673 units. The FEA model is shown in figure 1.

![Figure 1. FEA mesh grid for the heat cover.](image)

2.2. Load distribution

The upper side surface of the head cover of Francis turbine shall bear the weight of guide vane, sleeve, control ring and bearing, and a constraint condition is applied to the joint position of the head cover and seat ring. The lower surface should bear different water pressure inside and outside of the movable guide vane. The radial direction of the head cover shall bear the upper shaft sleeve support reaction and the intermediate shaft sleeve support reaction of the guide vane. Figure 2 is a schematic diagram of load and constraint. Among them, the weight of single guide vane and sleeve $G_1 = 38.38$ kN, the weight of control ring $G_2 = 171$ kN, the weight of bearing $G_3 = 18.3$ kN, the upper shaft sleeve support reaction of the guide vane $F_1 = 91000$ kN, and the intermediate shaft sleeve support reaction of the guide vane $F_2 = 174000$ kN. The regional water pressure at each position is measured under operating condition, where $P_1 = 55.5$ m, $P_2 = 44.4$ m and $P_3 = 18.5$ m.

| Modes | Frequency / Hz (Weight is loaded by gravity) | Frequency / Hz (Weight is loaded as a particle) |
|-------|---------------------------------------------|-----------------------------------------------|
| 1     | 40.2                                        | 28.8                                         |
| 2     | 72.5                                        | 56.4                                         |
| 3     | 120.8                                       | 70.8                                         |
| 4     | 124.4                                       | 76.8                                         |
| 5     | 131.1                                       | 78.9                                         |
The choice of loading method has obvious influence on the calculation result of natural frequency. The calculation results of the natural frequencies of the mounting weight loaded in the form of particles and in the form of gravity are compared in table 1. The results derived from the two loading methods are greatly different, which indicate a reasonable choice of loading method is very important to estimate the natural frequencies after the head cover is reinforced.

2.3. Modal testing
In order to choose the reasonable loading method, modal testing was carried out before head cover reinforcement. The loading method was modified by the experimental measurement results of the modal analysis. The natural frequencies and mode shapes of the head cover were obtained by using the broadband excitation method. The head cover is simplified as a single plane structure. Moving hammer strike and fixed point collection are used to conduct modal test on the head cover. There are 12 radial ribs on the head cover, and 5 test nodes are set along each rib (radial direction of the hydropower unit). The total number of test nodes is 60 as can be seen in figure 3.
Through modal testing, first three orders of natural frequencies and mode shapes of the head cover are obtained (table 2 and figure 4).

| Modes | Frequency / Hz | Description |
|-------|----------------|-------------|
| 1     | 39.93          | axial extension |
| 2     | 60.64          | two quadrants deflection |
| 3     | 151.35         | four quadrants deflection |

Figure 4. Mode shapes of head cover generated from modal testing before reinforcement

According to the actual situation on site, weight should be loaded in the form of particle rather than simply in the form of gravity. Loading method of FEA model was finally determined as 40% of the guide vane, bearing and control ring weight, which was loaded in the form of particle. The results comparison in table 3 indicates that the first two calculated frequencies are close to the measured ones.

| Modes | Calculated frequency / Hz | Measured frequency / Hz | Deviation / % |
|-------|---------------------------|-------------------------|---------------|
| 1     | 39.9                      | 36.3                    | 9.0           |
| 2     | 60.6                      | 66.5                    | 9.7           |
| 3     | 151.35                    | 101                     | 33.3          |

3. Natural frequencies prediction after head cover reinforcement
FEA model of head cover was modified by the experimental measurement results. Loading methods remain unchanged, and natural frequencies of reinforced head cover were calculated accordingly (see table 4). After reinforcement, head cover natural frequencies avoid turbine rotation frequency (1.56 Hz), guide vane over-flow frequency (37.5 Hz), runner blade frequency (20.3 Hz), and active guide vane Karman vortex frequency (101.6-104.6 Hz), which meet the requirements of normal operation. Meanwhile, head cover stiffness is improved, and head cover deformation is reduced consequently.
Table 4. Calculation results of the natural frequencies after reinforcement

| Modes | Calculated frequency / Hz | Description    |
|-------|---------------------------|----------------|
| 1     | 54.5                      | axial extension|
| 2     | 78.9                      | two quadrants deflection |
| 3     | 111.7                     | four quadrants deflection |

4. Effectiveness evaluation of head cover reinforcement

In combination with the maintenance opportunity, the head cover was reinforced by welding and plugging the apertures of stiffened plate. After the treatment, modal testing and vibration testing were implemented, and effectiveness of reinforcement was evaluated accordingly.

4.1. Modal testing of reinforced head cover

First three natural frequencies of the head cover were obtained and compared with the simulation ones. The results show that the calculated results of the first and second frequencies are close to the measured results.

Table 5. Comparison of calculated results and measured results after reinforcement

| Modes | Calculated frequency / Hz | Measured frequency / Hz | Deviation / % |
|-------|---------------------------|-------------------------|---------------|
| 1     | 59.1                      | 54.5                    | 7.8           |
| 2     | 89.7                      | 78.9                    | 12.0          |
| 3     | 183.8                     | 111.7                   | 39.2          |

4.2. Vibration testing of reinforced head cover

In order to ensure consistency, the stability test water heads before and after reinforcement were chosen to be the same. The test results in figure 5 show that the vibration of the head cover has been significantly improved after the head cover is strengthened. With the same operating condition, the vertical vibration of the head cover has a maximum reduction of 73.6%, and an average reduction of 51.5%. Under the test water head, the vertical vibration meets the national standard requirements within full power load segment.

Figure 5. Contrast diagram of vertical vibration of head cover before and after reinforcement

5. Conclusion

In this paper, the accuracy of FEA model is confirmed by comparing the modal parameters predicted by the model with the modal parameters identified by modal testing. The natural frequencies of the head cover before and after reinforcement are obtained, and the resonance risk caused by the close proximity...
between the natural frequency of the head cover and the water pressure pulsation in the flow passage is controlled simultaneously. The problem of excessive vertical vibration of the head cover is effectively improved by structural reinforcement. With the same operating condition, the vertical vibration of the head cover has a maximum reduction of 73.6%, and an average reduction of 51.5%. Under the test water head, the vertical vibration meets the national standard requirements within full power load segment.

References
[1] Jia, Y., Li, F., Wei, X. Li, X., Li, Z. (2017) A method for analysis of head cover deformation and vibration amplitude in Francis hydro-turbine system by combination of CFD and FEA. J. Mech. Sci. Technol., 31: 4255–4266.
[2] Wang, Y. (2013) Dynamic harmonic response analysis of head cover of hydraulic turbine. Proceedings of the 19th Symposium on China Hydropower Equipment, 218-223 (in Chinese).
[3] Xiong, L., Qian Q. (2006) Structural Dynamic Analysis on Head Cover of Gezhouba Water Turbine Set. J. of HUST. (Urban Science Edition), 23:25-29 (in Chinese).
[4] Ramsey, K.A. (1983) Experimental modal analysis, structural modifications and FEM analysis on a desktop computer. Sound Vib., 17: 19-27.
[5] Chhetry, B., Thapa, B., Thapa, B.S., Koirala, R. (2018) Design optimization of head cover of vertical francis turbine from maintenance perspective in context to sediment laden river projects. Fluid Mech. Res. Int., 2:13–20.