Stress Characteristics Analysis of Key Stationary Structural Components of Pump-Turbine Units Under Extreme Conditions

Yunfeng Xiao, Dehao Zhang, Xingxing Huang, Zheng Li, Zhengwei Wang, Yan Wang, and Biao Wang

Abstract The endurance and stability of the key stationary structural components are extremely important for the safe operation of the pump-turbine unit and the pumped storage power station. In order to reduce the stress level on the stationary structures during the design phase, the 3D finite element simulations of a large high-head pump-turbine unit under extreme conditions have been performed with a series of improvements on the design model. The full-scale 3D model of the stationary structures of the pump-turbine unit including the head cover, stay ring, stay vanes and bottom ring was built and meshed properly. After applying the pressure load of the extreme conditions on the structural finite element model, the stresses of the stationary structural components were calculated. According to the simulation results, all the locations where the maximum stress was above the material tensile strength can be improved. The novel optimized design approach developed in this investigation can highly reduce the design time cost and improve the endurance and stability of the designed structures to withstand all possible pressure loads under various steady and transient operating conditions. It also offers a valuable reference to the design of other types of hydraulic machinery.

Keywords Stress characteristics · Stationary structural components · Head cover · Pump-turbine · Extreme conditions

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1 Introduction

The worldwide energy crises we are facing nowadays are rooted in the reliance on fossil fuels such as coal, oil, and natural gas for energy production. The burning of fossil fuels for energy generation is a major source of air pollutants, including carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter. These pollutants contribute to air pollution, climate change, and various health and environmental problems. To solve these problems, the Paris Agreement adopted in 2015 encourages the deployment of renewable energy technologies as a means to reduce greenhouse gas emissions. Increasing the share of renewable energy such as solar power, wind power, and hydropower not only supports the goals of the agreement but also enhances energy security and reduces pollution. By diversifying energy sources and promoting renewable energy, countries can mitigate the impact of energy crises and reduce the pollutants associated with fossil fuel combustion.

Renewable energy sources such as wind energy and solar energy are highly dependent on the weather and are unstable. Pumped storage power stations serve as large-scale energy storage facilities, allowing excess electricity to be stored and dispatched when needed. This helps to balance intermittent renewable energy sources like wind and solar power, which can experience variability in their output. Pumped storage power stations can also help stabilize the power grid by providing a rapid response to fluctuations in electricity supply and demand. They can quickly release stored energy to the grid when demand is high or absorb excess electricity when demand is low, helping to maintain grid frequency and stability.

In order to store electric energy with a large capacity, the pumped storage power station often has a high water head, that is, the water level difference between the upper and lower reservoirs. The maximum water head can reach about 800 m, so the pressure acting on the pump-turbine unit is also very high, which can induce high stresses on the stationary and rotating structures of the pump-turbine unit.

Serious accidents have occurred in many large hydropower stations due to pressure-induced high-level stresses. The accident at the Sayano-Shushenskaya hydropower station in Russia in 2009 was caused by the failure of the head-cover bolts of a turbine unit, resulting in a massive explosion and subsequent flooding of the power station. The incident claimed the lives of 75 people and caused extensive damage to the facility, leading to a prolonged shutdown for repairs [1]. A similar incident occurred at a pumped storage power station in China in 2016, where the head cover and rotor were lifted by high-pressure water, and eventually gushed into the power station house [2]. Strong vibrations and fatigue damage on the pump-turbine unit are also not uncommon [2–6]. So the durability and stability of key structural components like head covers are extremely important for the safe operation of pump-turbine units and pumped storage power stations.

This paper researches the pressure-induced stress on the key stationary structures of a high-head pump-turbine unit. A full-scale 3D model of the stationary structure of the pump-turbine unit (including the head cover, stay ring, stay vanes, and bottom ring) was constructed to carefully analyze the potentially high stress concentrations caused by the pump-turbine under extreme conditions.

2 The Investigated Pump-Turbine Unit and Methodology

2.1 Model of the Pump-Turbine Unit

The pump-turbine unit in the pumped storage power station involves the use of water and gravity to store and generate electricity. It is a highly efficient and widely used method for balancing and stabilizing the electrical grid, particularly during periods of high demand or intermittent renewable energy generation. The storage power station in this research has two water reservoirs located at different elevations. 4 reversible pump-turbine units are installed in the power plant. The main parameters of investigated pump-turbine unit are listed in Table 1.

When there is excess electricity available in the grid, typically during off-peak hours or when renewable energy sources are producing surplus power, the excess electricity is used to pump water from the lower reservoir to the upper reservoir, thus storing potential energy. During periods of high electricity demand or when additional power is needed in the grid, the stored water in the upper reservoir is released back to the lower reservoir through the pump-turbine units, generating electricity as it flows downhill. So the pump-turbine units act as both pumps and turbines, allowing for the reversible flow of water between the reservoirs.

In this study, the full-scale 3D CAD model of the stationary structures of the pump-turbine unit has been built. The model includes the head cover, stay ring, stay vanes, and bottom ring as shown in Fig. 1.

Table 1 The parameters of the pump-turbine unit

Parameter	Value
Rated head (Hr)	440 m
Maximum head (Hmax)	482 m
Unit capacity	350 MW

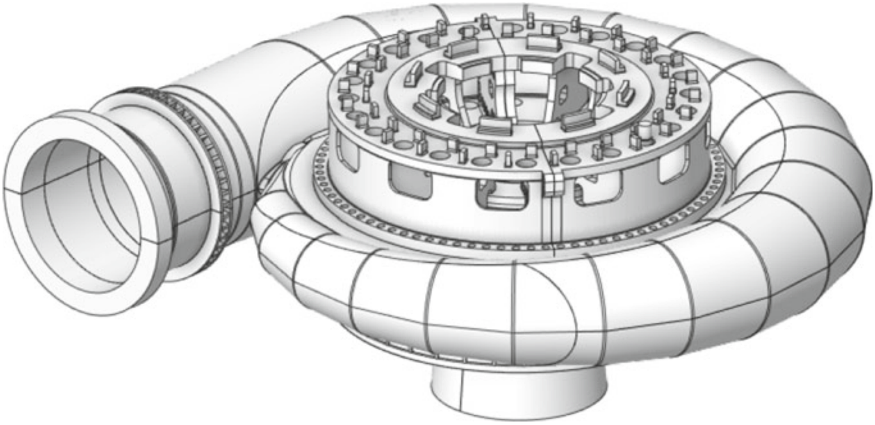

Fig. 1 The CAD model of the stationary structure of the pump-turbine unit

2.2 Governing Equation and Calculation Setup

The Finite Element Method (FEM) is used in this study to calculate the pressure-induced stresses on the stationary structures of the pump-turbine unit. FEM is a numerical technique widely used to solve complex engineering problems by dividing a domain into small finite elements.

The discrete structural equilibrium equation based on FEM is described as:

$$M\ddot{x} + C\dot{x} + Kx = F(t) \tag{1}$$

where M is the mass matrix of the structures, C is the damping matrix, and K is the stiffness matrix. $\ddot{x}$, $\dot{x}$ and x are the acceleration, velocity and displacement vectors of the structures, respectively; $F(t)$ is the external excitation loads on the structures including pressure load, gravity, etc. t is the time.

During the transient processes of the pump-turbine unit such as startup, stop down, load rejection and runaway, the water hammer appears in the water pipes of the pumped storage power station. Water hammer is a hydraulic phenomenon that occurs when there is a sudden change in the velocity or flow of fluid in a water piping system, resulting in a pressure surge or shockwave. The transient processes are extreme conditions for the pump-turbine unit that can lead to significant pressure fluctuations, and induce high mechanical stresses on the structures of the unit [7–11].

The finite element model of the stationary structures of the pump-turbine unit is created as shown in Fig. 2. In order to obtain more accurate results, the mesh of the local stress concentration area of the head cover and chamfer radius of the stay vane was refined.

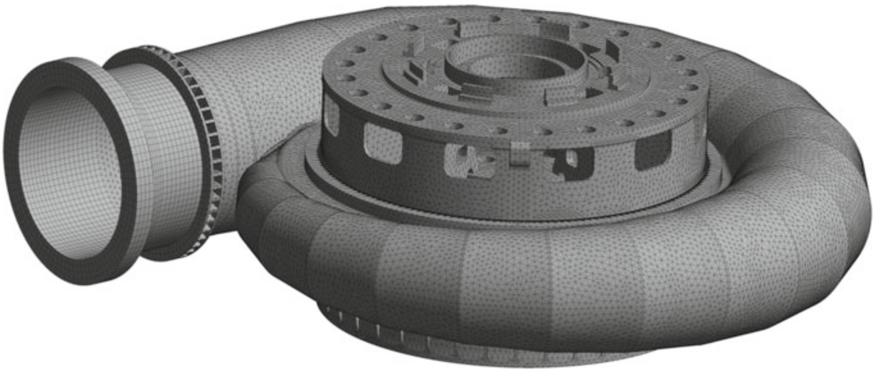

Fig. 2 The mesh of the stationary structures of the pump-turbine unit

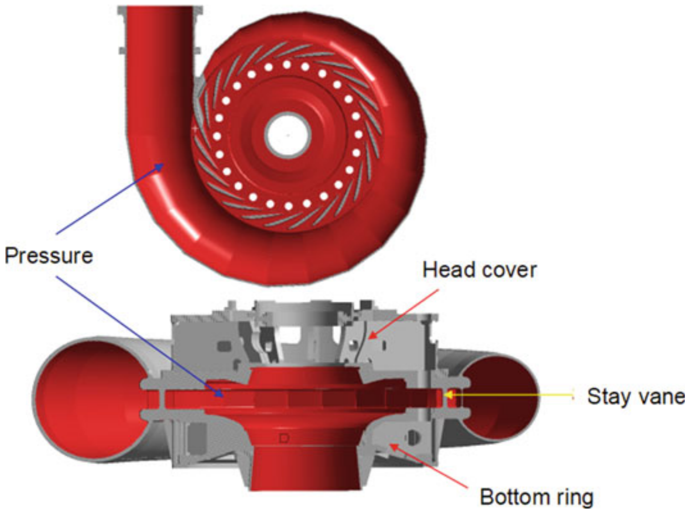

Fig. 3 The boundary conditions on the stationary structures of the pump-turbine unit

The pressure level can reach 1.5 times the maximum head (Hmax) of the pumped storage power stations under extreme conditions during start-stops, load rejection, and runaway. Figure 3 shows the boundary conditions on the stationary structures of the pump-turbine unit.

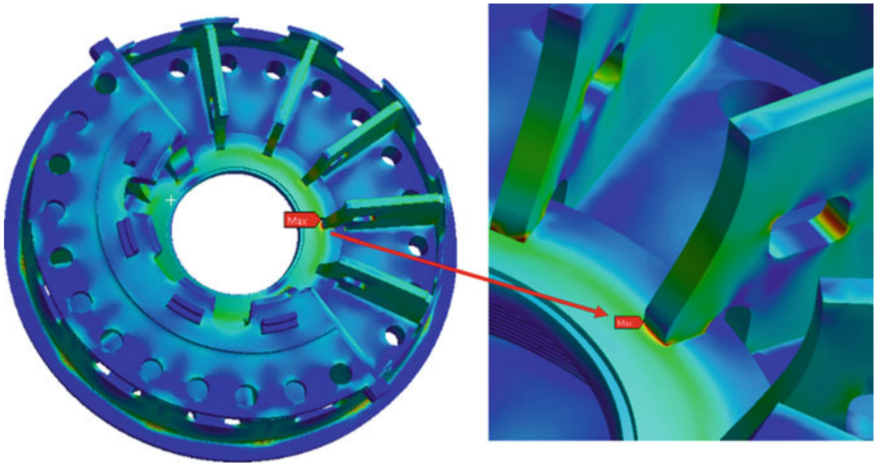

Fig. 4 The pressure-induced stress distribution on the head cover of the pump-turbine unit

2.3 Results and Discussions

By applying the pressure distribution on the stationary structures of the pump-turbine unit under extreme conditions with 1.5 times the maximum head, the corresponding stress analysis results of the stationary structures including the head cover, stay ring, stay vanes, and bottom ring.

It can be seen from Fig. 4 that the local stress concentration is located at the connection between the head cover reinforcing plates and the inner head cover. The stresses in the red area are all larger than the tensile strength of the material, which has to be improved. It is recommended to add chamfers at the connection between the head cover reinforcing plates and the inner head cover to reduce the maximum stress on the head cover properly.

The local stress is concentrated at the chamfer radius of the stay vane as shown in Fig. 5. The maximum stress value is less than the tensile strength, which is safe under extreme conditions.

Figure 6 shows that the local stress of the bottom ring is concentrated at the rounded corner of the lower plate of the bottom ring, and the maximum stress value is less than the tensile strength, so the design is also safe under extreme conditions.

3 Conclusions

This paper investigates the pressure-induced stress characteristics of key stationary structural components of a high-head pump-turbine unit under extreme conditions during the transient processes. The full-scale CAD model and finite element model

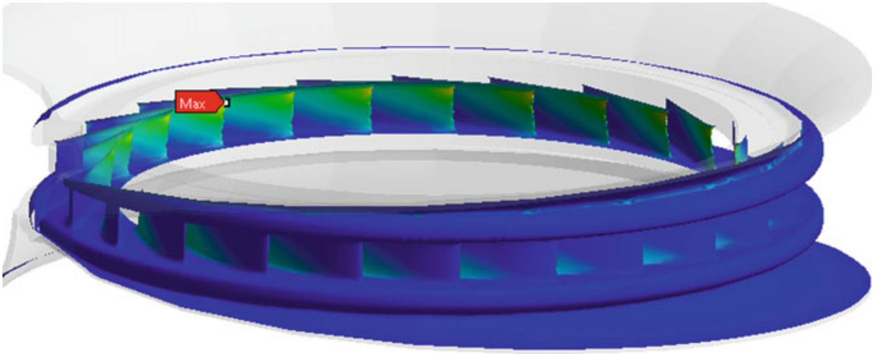

Fig. 5 The pressure-induced stress distribution on the stay ring and stay vanes of the pump-turbine unit

Fig. 6 The pressure-induced stress distribution on the bottom ring of the pump-turbine unit

of the head cover, stay ring, stay vanes and bottom ring were created properly. After applying the pressure load of the extreme conditions on the finite element model with 1.5 times the maximum head, the maximum stresses of the stationary structures of the unit pump-turbine have been calculated.

The local stress concentration of the head cover is at the connection between the head cover reinforcing plates and the inner head cover. And the local stress is concentrated at the chamfer radius of the stay vane and at the rounded corner of the lower plate of the bottom ring.

The maximum stresses of the stay vane and bottom ring are less than the tensile strength of the material. However, the maximum stress of the head cover is larger than the material tensile strength, which is not allowed. It needs to add chamfers at the connection between the head cover reinforcing plates and the inner head cover so that the maximum stress on the head cover can be reduced properly.

This novel optimized design approach can efficiently reduce the design time cost and improve the endurance and stability of the designed structures to withstand all possible pressure loads under various operating conditions. This approach can be used in the design of other types of hydraulic machinery.

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Conflicts of Interest The authors declare that they have no conflicts of interest to report regarding the present study.

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