The coupled dynamic analysis of hydroelectric unit and powerhouse considering the bolt connection characteristics

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Abstract. As the increasing of the capacity and water head of the hydropower stations, the hydroelectric unit’s vibration and its induced powerhouse vibrations become a critical problem. The system of hydraulic-mechanical-electric-structural is coupled and with strong non-linear characteristics. The frame and head cover are all connected with the powerhouse pier via high-strength bolt. The paper is concentrated on the dynamic coupling mechanism and simulation model considering the bolt’s connection and load transmission characteristics. With the theory analysis and numerical simulation, the connection and transmission behaviour of the high-strength bolt would be studied and a more accurate and simple mechanical expression would be derived. The connection sliding law and dynamics modelling method of bolts are discussed. Based on the displacement-load curve of single lap and single bolt analysis it is concluded that the increasing preloading will improve the tangential bearing capacity of the bolted joint connection. Then the FEM coupling model of the lower bracket and powerhouse is established with the virtual medium method. Based on the free-vibration and dynamic response analysis the effects of the loosening of the bolt on the static stiffness of the coupling structure are discussed. The von-Mises stress’s increasing due to some of the bolt’s loosening would result to the material fatigue damage. Finally five preloading schemes of the bolts are discussed and the simulation results show that the preloading force has a greater lateral impact on the structure than on the longitudinal direction. The preloading force improves the coupling structure’s stiffness and reduces the vibration amplitude of the frame. As for the preloading force, when it is small the connection effect is not strong enough and the vibration level may be higher, so the actual preloading state should be exactly simulated. When the bolt preloading reaches 60-70% of the material yield strength, the rigid connection can be directly used in the modelling for the convenience of calculation.

1. Introduction
The vibration of hydro-turbine and powerhouse structure is inevitable, especially for the large-scale hydropower stations and pumped-storage power stations, and sometimes could be very serious and critical. The unit vibration is firstly harmful to the mechanical system, and then may be transferred to the concrete supporting structures of the powerhouse through some path, which is called unit-induced-vibration [1]. So the shaft system and the supporting structure is a coupling system, and the transformation of static forces and vibration energy is mainly rely on bearings, bracket, head cover, stator base and stay vanes. The connections of those supporting parts are mainly via high-strength bolts. Statistics suggest that there may have more than 5000 bolts for a large water turbine, and its machining quality and setting accuracy are very important to the unit’s total performance. All the bolts would be in the vibration surroundings in the unit operation conditions. Long-term effects of the vibration would result to the creep deformation, loose, shear off and crack. A typical example is the catastrophic accident took place in Sayano-Shushenskaya Hydropower Station, which origin was the shear off of the head cover’s bolts due to the water hammer of the turbine. So for the structure analysis, vibration forecasting and regulating, the bolt connection characteristics are very critical.
In the large hydropower stations, high-strength bolts are used generally because of the large scale and heavy load. There exist many complicated effects such as preloading, friction and gap for the connection and load transferring. For the bolt connection there exist deformation, contacting, friction slippage and stiffness, belong to a complicate contact nonlinear problem. There were some calculation models, such as Iwan model. The theoretical analysis is very difficult and then numerical simulation becomes preferred, such as FEM model, cohere method, EVC method, spring-damping method, BEAM element and virtual material hypothesis-based dynamic model. During dynamic movement it was considered that the load is transmitted by the bolt’s winding and expanding. In the numerical model the stiffness connection and the contacting bound between two plates was released, the simulated results were coincide very well with the theory resolution. In reference 9 the preloading was simulated with the function of Fastner in software of PANRAN, and the error with experiment results was less than 10%. But in the above methods the preloading was fixed and only was suit to the static analysis.

The system of hydraulic-mechanical-electric-structural is coupled and with strong non-linear characteristics. The frame and head cover are all connected with the powerhouse pier via high-strength bolt. There had few research results about the connection stiffness and force transmission characteristics of the bolts, especially under the vibration conditions. In this paper the research is concentrated on the dynamic coupling mechanism and simulation model of the coupling system of unit shaft system and powerhouse. With the theory analysis and numerical simulation, the connection and transmission behaviour of the high-strength bolt would be studied and a more accurate and simple mechanical expression would be derived.

2. Virtual medium model and its application for high-strength bolt

The virtual medium method is a new model to simulate the bolt connection surface of bolt and the surface’s interaction is defined with a thin layer material with fixed thickness. The physical and mechanical properties of this material could be adjusted to truly express the bolt connection characteristics.

The simulation model of the virtual medium equivalent to the bolt joint surface could be expressed as following formula. It is seen that the elastic modulus and Poisson ratio of the virtual medium are only related to the elastic modulus $E_1$ and $E_2$, Poisson ratio $\mu_1$ and $\mu_2$, surface roughness $Ra_1$, $Ra_2$ of the two connection pieces of the bolt, and the normal load $P$ acted on the joint surface. The thickness $h$ is decided by the standard deviation $\sigma_p$ of the two contacted surface roughness peak height $d$ and maximum theory space between the connection surfaces. The density $\rho$ depended on the two connection piece’s density of $\rho_1$ and $\rho_2$.

$$E = E \left( E_1, E_2, \mu_1, \mu_2, Ra_1, Ra_2, P \right)$$
$$\mu = \mu \left( E_1, E_2, \mu_1, \mu_2, Ra_1, Ra_2, P \right)$$
$$h = h \left( \sigma_p, d \right)$$
$$\rho = \rho \left( \rho_1, \rho_2 \right)$$

In order to check the availability of the virtual medium method, an independent bolt with two connection board is studied and a three-dimensional FEM model is constructed with ANSYS software, under actions of preloading and tangential force. Two plates and the bolt are all steel with elastic modulus 210GPa and Possion ratio 0.3. The plate size is 100mm×60mm×10mm, and the overlap length is 40mm. The high-strength bolt is M16. The FEM model is shown in figure 1 with 9394 nodes and 11101 elements. The element TARGE170 and CONTA174 are used to simulate the contact surface with friction coefficient of 0.25. The preloading is 30N·m and the uniformly distributed tangential load is 30kN.
The elastic modulus and Possion ratio of the virtual medium material are 3.93GPa and 0.12 respectively based on formula (1), and its density is 7850kg/m³ and the thickness is defined as 1mm. Listed in table 1 are the first fourth natural frequencies of the model. Here the solid model is the FEM method used by reference 11, MPC method is Multi-Points-Constraint method. The virtual method is based on formula (1) and used in this paper. The error of each method is the percentage compared with the results of solid method. It is seen that the virtual medium method have much more accuracy compared with other methods.

![Figure 1. FEM Model of a bolt and the connection board](image)

The natural frequencies have positive correlation with the preloading. It could be concluded that the stiffness of the bolt connection increased with the higher preloading. So in the dynamic analysis the preloading of the bolt must be taken into consideration.

### Table 1. Comparison of natural frequency of different methods (Hz)

| solid model | cohere method | MPC method | spring-damping method | virtual medium |
|-------------|---------------|------------|-----------------------|----------------|
|             | result        | result     | result                | result         |
|             | error         | error      | error                 | error          |
| $f_1$       | 313.59        | 309.78     | 306.26                | 316.56         |
|             | 3.4%          | -1.2%      | -2.3%                 | 1.0%           |
| $f_2$       | 1013.2        | 1139.5     | 1186.6                | 1204.8         |
|             | 50.5%         | 12.5%      | 17.1%                 | 17.9%          |
| $f_3$       | 1651.2        | 1595.8     | 1497.0                | 1832.6         |
|             | 20.9%         | -3.4%      | -9.3%                 | 11.0%          |
| $f_4$       | 1873.4        | 1640.4     | 1622.3                | 1944.4         |
|             | 16.8%         | -12.4%     | -13.4%                | 3.8%           |

### Table 2. Comparison of simulation frequencies and experimental frequencies (Hz)

| preloading moment | 3N m | 6N m | 9N m |
|-------------------|------|------|------|
|                   | test | test | test |
|                   | result | numerical | error | numerical | error | numerical | error |
| $f_1$             | 92.45 | 91.09 | 1.47% | 94.12 | 1.60% | 97.06 | 3.03% |
| $f_2$             | 211.37 | 203.57 | 3.69% | 213.48 | 4.11% | 218.91 | 5.36% |
| $f_3$             | 248.41 | 249.53 | 1.14% | 264.33 | 5.93% | 264.58 | 5.65% |
| $f_4$             | 354.28 | 355.27 | 1.32% | 351.06 | 1.19% | 358.89 | 1.91% |

### 3. The effect of the bolt preloading on the stiffness of the spider and pier structure

#### 3.1 The stiffness of the spider

A powerhouse structure is took 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 lower spider were shown in figure 2 and figure 3. Figure 4 is the serial number of the contact surface. Every spider beam is connected with basement with four M64 high-strength bolts.
Four situations of the preloading are assumed to study the effects of the bolt loosening, and the corresponding mechanical parameters are obtained based on formula (1) as shown in table 3. Here the preloading is defined by the ratio of the preload with the steel yield strength of 640N/mm², and the maximum preloading is set to design value of 70%. Under the actions of vertical load of 19400 kN and total centrifugal force of 2910 kN, the minimum shaft stiffness and radial stiffness are shown in figure 5 and figure 6 respectively. It could be seen that the spider stiffness with bolt connection is closely related to the preloading, which is decreased with the bolt loosening and the maximum decrease is
17.08% when preloading is only 10% of the yield strength. The maximum stress of the spider is 155 MPa, less than the material standard strength.

Table 3. The inherent property of virtual material

| Preloading | 10%  | 50%  | 60%  | 70%  |
|------------|------|------|------|------|
| Preloading moment (N·m) | 2193 | 10961 | 13153 | 15345 |
| Preloading (kN) | 171.3 | 856.3 | 1027.6 | 1198.8 |
| Elastic modulus (GPa) | 4.92 | 11.12 | 12.20 | 13.19 |
| Poisson's ratio | 0.15 | 0.22 | 0.22 | 0.23 |

Figure 5. The minimum shaft stiffness of the spider related to the preloading

Figure 6. The minimum radial stiffness of the spider related to the preloading

3.2 The pier stiffness

The unit bracket is fixed on the concrete pier through basement plate and bolt, which is a coupling system. The stiffness of the pier is under the influence of the bolt connection, and the bracket could increase the stiffness of the pier in some extent. The pier stiffness could be calculated under different preloading in two directions, as shown in figure 7 and figure 8. It is seen that the loosening of the bolt is also unfavourable to the structure’s stiffness.
The unbalance load of the shaft is transferred to the pier through the bracket arms. When the preloading of all the bolts is 70% of the steel yield strength, namely the standard conditions, the force distribution is almost uniform for all the 12 arms, from 18.1kN at arm 5 to 20.9KN at arm 12. The unbalance load is acted along the direction of arm 12 so the reaction force of arm 12 is the maximum and arm 5 is the minimum in the opposite position.

If the loosening is happened in the bolts of arm 12, the reaction distributions of the 12 arms would be changed with the decreasing of the preloading, as shown in figure 9. The range of reaction decreasing of arm 12 is reached to maximum of 86.37% when preload decreased to 10%. In contrast the reactions of arm 1 and arm 11 nearing the arm 12 increased rapidly with maximum of 24.64%. So it could concluded that if the loosening is happened in some arm’s bolts, the reaction forces in the near arms could be increased and the distribution of arm’s reactions would be no longer uniform. This situation is certainly not favourable to the safety of the bolts and also of the coupling structures.
4. Coupling vibration analysis of the bracket and pier supporting system

Taking the unbalance dynamic forces in radial and tangential direction acted on the bracket being 76kN and 38kN respectively and the excitation frequency being 1.5625Hz, the dynamic displacement of the lower bracket basement could be obtained, as shown in figure 10. As the decreasing of the bolt preloading the overall displacement of the pier foundation is decreasing also, reached to maximum of 67% in conditions of 10% preload, comparing with the conditions of 100% preloading. It is also seen that the displacement of 70% preload is also same as that of 100% preload, so when the preloading could be kept in 70% the bolt connection would be treated as a rigid joint.

![Figure 9. The bracket arm force distributions under different preloading](image)

![Figure 10. The bracket basement dynamic displacement under different preloading](image)

But for the unit bracket, the displacement of the arm end is increasing obviously with the decreasing of the preload, as shown in figure 11. In the extremely situation of 10% preloading the maximum displacement reached to 552 \(\mu\)m, when the preload being 70% the value being only 4.39 \(\mu\)m. It could be concluded that there had slippage happened between the contact surfaces of basement plates under the loosening condition of the bolt connection. So the preload keeping is very important to the supporting stiffness and vibration controlling.
5. Conclusions

Through the research works it could be concluded that the virtual medium method is suitable to the simulation of coupling structure with a lot of bolt connections, which advantage are the simplicity of simulating model and the easy availability of the medium’s characteristics via the parameter of connection parts. With this method the preloading could be taken into consideration and there have higher accuracy based on the model analysis and comparison with the experiment results. The results show that the preloading has positive effect on the bolt connection stiffness and must be considered in the static and dynamic analysis of the coupling structure.

The bolt loosening would result to the stiffness decreasing of the bracket and the pier supporting systems. Under the dynamic excitations the pier vibration amplitude would decreased and the bracket vibration would be increased remarkably. So if some bolts are loosed the dynamic stresses of its neared foundations would become larger and there have the possibility of fatigue failure.

When the bolt preloading reaches 60-70% of the material yield strength, the rigid connection could be directly used in the modelling for the convenience of calculation.

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