Energy flow transmission analysis on the powerhouse vibration under turbine hydraulic loads

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Abstract. The vibration of the powerhouse in hydropower station mainly originated from the dynamic loads of turbine and generator set. In the vibration conductivity path there have gain amplification or reduction, so the transmissibility analysis and the transfer path recognition are very important to the vibration analysis and its treatment. Based on energy flow finite element methods, the vibration transmissibility of the powerhouse under turbine dynamic loads was analyzed in this paper. Firstly, the energy transfer characteristics of the different slab structures were analyzed and the results could provide some valuable helps for the vibration control. Secondly, vibrational power flow from spiral case into the upper structures such as pier, wind cover, slab and wall were studied. It is concluded that the supporting structure are the main path for the energy flow, and the reduction effects of the thick slab and wall are much more remarkable. Finally, the law of dominant path recognition was first proposed with a numerical solution. The vibration transmission from the main hall to the auxiliary power house was calculated for the different paths such as joint, foundation and rock around. The results indicated that as a kind of structural joint filler, the closed-cell foam could actively restrict the vibration transmission.

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 vibration identify and reduction have become a research focus for the researchers and engineers over a long period of time [1]. The vibrations of generator unit are originated from the mechanical, electrical and hydraulic unbalance, and the hydraulic pulsation is the main excitation resource. The unit vibration is firstly harmful to the mechanical system, and then may be transferred to the concrete supporting structures of the power house through some path, which is called unit-induced-vibration. So the identifying of the vibration source and its transfer path are very important to the vibration induction and optimal design.

Vibration transfer path analysis is belong to the research field of vibration control. For a dynamic system, any excitation must causes the response, and the presentation of this relationship is the transfer rate function. The Transfer Path Analysis (TPA) is a vibration research method coupling the test results and numerical simulation to propose and evaluate the dynamic response and then to determine the transfer path, excitation resources and to perform the dynamic optimal design. In the earlier time the power flow method was mainly used in the vehicle’s vibration and noise analysis [2]. As there existed difficult for the measuring of transfer function and identifying of dynamic load, the method of power flow considering the coupling effect between vibrators [3]. More practical methods were developed and were used in the area of mechanical system, bridge and hydropower engineering,
mainly included mobility energy flow method, statistical energy analysis (SEA) and structural intensity analysis (SAI). For the powerhouse in hydropower stations which is a very complicated coupling dynamic system, the traditional energy flow methods may be not suitable again. At present time the dynamic analysis must include the coupling of hydraulic, mechanical, electrical and structural sub-systems [4]. Based on the coupling simulation, the power flow finite element analysis (PFFEA) becomes an effective method for the structure vibration transmission analysis. The power flow method could deal with the concentration properties of the vibration modals [5-7], so generally being utilized in the analysis for the coupling vibration between the generator unit and powerhouse [8, 9].

The FEM power flow method is used in this paper to identify the vibration transfer path of the hydraulic oscillations to the powerhouse structures, also included the vibration transmission from main powerhouse to auxiliary powerhouse structures. The research object is to identify the excitation resources and its dominant or mainly transfer path. The research results would be very valuable to the vibration evaluation, fault diagnosis and design optimization of the hydropower stations.

2. Theory and its solution of vibration power flow section of your paper

2.1. Power flow theory

Power is the work of a dynamic load done during unit time in the $i$th node interval, as defined by equation (1). So it is a coupling characteristics of the dynamic load and the system response, and also its impedance property. For the vibration transmission analysis, it is very important to identify the power flow transfer path. If the summery of the power flow through a special area or point during a time of period is calculated, the path power flow transfer ratio would be identified. For a harmonic dynamic excitations, the system dynamic response would be also harmonic form and could be obtained by equation (2).

$$ P_i = F_i \cdot V_i $$

$$ P_i = \frac{1}{T} \int_0^T |F_i| \cos \omega t \cdot |V_i| \cos(\omega t + \phi) dt = \frac{1}{2} |F_i| \cdot |V_i| \cdot \cos \phi $$

Where $P_i$ is the power flow in one time cycle, $F_i$ is the dynamic load and $V_i$ the velocity response, $\omega$ is the angular frequency, $\phi$ is the phase angle of the response and load. With complex calculation formula (2) could be expressed as follows,

$$ P_i = \frac{1}{2} \text{Re} \{F_i \cdot V_i^*\} = \frac{1}{2} \text{Re} \{F_i^* \cdot V_i\} = \frac{1}{2} |F_i|^2 \cdot \text{Re} \{\beta\} $$

Where the symbol "*" means a conjugate vector. $\beta = V/F$ represent the structure impedance and could be measured by experiment or numerically simulated. In the frequency domain, $P$ could be a power flow spectral density function and in the time domain it is a time function.

With a finite element model of a structure system, the dynamic equilibrium equation as follows could be solved and the node displacement $u$ and node force $F$ were obtained. Then the node velocity $V = -j\omega U_i$ in complex form could be got.

Based on equation (3) the power flow of a node could be calculated in the FEM model, with a post-processing project for the FEM solution.

$$ P_i = \frac{1}{2} \text{Re} \{F_i \cdot V_i^*\} = -\frac{\omega_i}{2} \text{Im} \{F_i \cdot U_i^*\} $$

2.2. Identifying of the dominant transfer path

For a complicate 3D system, there have very different dynamic transmission paths and where there exist largest power flow intensity would be looked as the dominant transfer path. The identifying and propagation limiting would be very significant for the vibration reduction and isolation.
2.2.1. Dominant power threshold value (DPTV)

Based on the significance test theory in mathematical statistics, the main transfer path could be discriminated with following expression,

$$ P \left\{ P_i > K \right\} = 1 - \alpha $$

(5)

Where $p_i$ is the node power flow value of FEM model, and $P$ represent the probability relative to a constant $K$, $\alpha$ is a significant factor.

Based on intermediate value theory, there must exist a power flow value $K(\alpha)$ at a specific node within the transmission region which satisfy equation (5), and this $K(\alpha)$ could be defined as the DPTV in this system.

2.2.2. Law of Dominant Path Recognition

For a 3D system the power flow transmission path must also be spatial. When the simulation is made with 3D FEM the solution is the node’s power flow, so this numerical simulation is called FEM power flow. If eight value of $\alpha=0.2 \sim 0.9$ is assumed, DPTV $K_\alpha$ could be calculated eight times separately, and eight transmission domains $\Gamma_\alpha$ are then be confirmed. The transmission intensity $PW_\alpha$ could be defined as following,

$$ PW_\alpha = \sum_{i=1}^{n_\alpha} p_i / \sum_{i=1}^{n_\alpha} \Gamma_i, \quad i=1,2,\ldots,n_\alpha $$

(6)

Where $PW_\alpha$ is the average power flow, $p_i$ is ith node’s power flow value, $\Gamma_i$ is the volume of the ith node, and $n_\alpha$ is the total node number of FEM model.

In order to recognize the dominant transfer path, a factor $\beta_\alpha$ is defined as $\beta_\alpha=\Delta PW_\alpha/\Delta PW_{\alpha-0.1}$, which is the transmission dominance ratio of the adjacent significance factor $\alpha$. $\Delta PW_\alpha=PW_\alpha-PW_{\alpha-0.1}$ is the power flow discrepancy within adjacent factor. If $\beta_\alpha\in(1.0, 1.5]$, the transmission region is defined as ordinary transfer path; if $\beta_\alpha\in(1.5, 2.0]$, looked as domain transfer path; as for $\beta_\alpha>2.0$ it is the absolute transfer path.

For a complicated coupling dynamic system such as the coupling system between generator unit and powerhouse, there must exist several different transfer paths. The recognition of dominant transfer path is very significant to the vibration diagnosis, isolation and reduction.

3. Pier vibration transfer path recognition in vertical direction

The hydraulic pressure pulsations are mainly acted on the turbine runner and flow path such as spiral case, head cover and draft tube. The dynamic pressure may excite the vibration of turbine directly and also the vibration of the concrete supporting structures, such as the head cover, bracket and pier. The simplified coupling system model of the shaft system and concrete supporting structure is shown in Figure 1. There exist mainly two transfer paths, first is from the spiral case (m8) and head cover (m6) to the pier (m7); the second is through the shaft system and the supporting components, runner (m3) – rotor (m2) – bracket (m5) – pier (m7). The coefficient $k$ is the stiffness of the shaft, rotor and racket beam, head cover; and $m$ represent the lumped mass of the parts.

For the two possible transfer paths from the turbine to the pier, the power flow could be obtained respectively as follows,

$$ P_{zhou} = \frac{1}{2} \text{Re}(F_{zhou} V_{zhou}) $$

$$ P_{ding} = \frac{1}{2} \text{Re}(F_{ding} V_{ding}) $$

(7)

Where $P_{zhou}$, $F_{zhou}$, $V_{zhou}$ is the power flow, force and velocity of the pier transferred from the shaft, and $P_{ding}$, $F_{ding}$, $V_{ding}$ is that from the head cover system.
The power flow transfer ratio is defined as \[ \beta = \frac{|P_{\text{out}}|}{|P_{\text{in}}|}. \]

Taking a practical hydropower station as the simulation example, and the pressure pulsation is simplified as a harmonic wave. The transfer ratio of the paths are shown in Figure 2, which indicated the transmissibility of each path at different excitation frequencies. It could be concluded that at the resonance point, the amplification coefficient reach the maximum. Considering the whole process of vertical vibration transfer, the transmissibility of the head cover is significantly smaller than that of the shafting system. Throughout the entire frequency range, the mean value of the path transmissibility ratio is 32.37. This indicates that the vibration effect of the head cover system could be neglected in practical case study.
If the transfer coefficient is defined as the ratio of amplitude of the vibration response force and the excitation force in the pier structure, as shown in Figure 3, the conclusion is that the effectiveness of the pressure excitation acted on the head cover is much larger than that of the shaft system.

4. Vibration transfer path of the generator floor
An open-air powerhouse of a large hydropower station is taken as a calculation example to examine the vibration transfer ratio from the turbine hydraulic excitation source to the slab structure of the generator floor level. The generator’s capacity is 700 MW. Shown in Figure 4 is the FEM model of the powerhouse. The boundary conditions of the FEM model are defined as follows: the bottom being fixed, the surrounding edges being with spring bars in normal direction or with free condition as for the structure joint. It is assumed there exist three direction’s vibration propagation, namely longitudinal, crosswise and vertical direction. Shown in figure 5 is the power flow distribution of the slab in three directions.
It could be concluded that the power flow distribution in the crosswise direction presents obvious structural effects, next is of the longitudinal direction’s distribution. It is seen that distributions were subdivided to some different regions by the beams under the slab. The columns, beams, and wind cowling have effectively stiffness supporting to the dynamic responses. The hoisting opening in the slab is the weak link, so the power flow in this area is confused and strengthened. The shear energy propagation is dominated and the maximum amplitude is $10 \sim 23.47$ W, mainly appeared in the link spot of beams and columns or the opening. The power flow transfer of the slab is mainly in the horizontal direction and the vertical direction’s power flow is mainly concentrated close to the wall of the wind cowling. So it may be suggested that for the slab vibration reduction the effective manners should be the increasing of the slab thickness and the stiffness of the beams and columns. Another way is to strengthen the connection of the different parts such as between beams and wind cowling or the wall.

5. Energy transmission from main powerhouse to auxiliary powerhouse
For an underground powerhouse with the unit’s capacity of 300 MW, generally the auxiliary hall is connected to main hall with a structural joint. The vibration of the main powerhouse may be transferred to the auxiliary structure path though the joint and the rock foundation. Sometimes the vibration and noise of the auxiliary structures such as slabs may be very seriously, so the identifying of the dominated transfer path would be very valuable to the vibration reduction and isolation. An underground powerhouse was taken as a numerical example as shown in Figure 6. The measured pressure fluctuations in the spiral case of the turbine model experiment were used as the excitation loads, with a dynamic pressure peak value of 0.153 MPa and the main frequency of 75 Hz, which were mainly excited by the interaction between guide vane and turbine blade.

![Figure 5. Power flow distribution in generator floor slab](image)

![Figure 6. Structural diagram of the main and auxiliary powerhouse](image)
The transfer ratio of the filling material in the structural joint could be defined as the ratio of the energy input and output of the slab edge of the main and auxiliary powerhouse. For the different filling material such as asphalt wood plate, rubber plate and closed-cell foam plate, their conductivity is always less than 10%. In this study the filling material is chosen as closed-cell foam plate, and is treated as a spring link element in the FEM model. The slabs in 1288 m level is taken as research object and the power flow calculation results of the nodes of the slab edge along the structural joint was displayed in Figure 7. It is seen that the distributions of the slab’s edges of the main and auxiliary powerhouse were not consistent and the power flow value in the main hall side is larger than that in the auxiliary side obviously. The peak value of the main powerhouse slab appeared near the columns, and that of the auxiliary powerhouse slab were close to the downstream wall, not along the joint edge.

![Figure 7. Power flow transmission distribution along the joint in Level 1288 m](image)

The dominant power flow threshold could be calculated for the auxiliary powerhouse slab. For the longitudinal and crosswise directions, the dominant transmission power flow was located all in the downstream wall and for vertical direction it is near the columns. The main energy input all originated from the downstream rock connected to the slab. The maximum threshold values in three directions were only $5.7 \times 10^{-3}$ W. So it is concluded that the joint is not the dominant transfer path and the filling material in the joint being an effective vibration isolation manner.

![Figure 8. distributions of DPTV in vertical direction](image)

The concrete of spiral case were connected with the rocks between 1275.8 m—1282.8 m level, which may be the dominant vibration transfer medium. The distribution of rock’s DPTV in the different vertical level was shown in Figure 8. It is seen that the peak values were between 1280 m level and 1295 m level, which is corresponding to the first floor up to third floor of the auxiliary powerhouse and the turbine floor up to the generator floor of the main hall. As for the low level rocks,
the threshold value is less than $3 \times 10^{-3}$ W. It is shown from Figure 6 that the concrete around the spiral case were connected with the rock downstream of the main powerhouse, located from 1275.8m to 1282.8m, and the dynamic transmission was higher here than that in other regions. From Figure 8, it could be concluded that the power transmission in the rock receded gradually with the higher elevation. The core vibration energy focused on the dominant transmission path and decreased gradually during its conductance. The rock from 1282.0m to 1295.0m had a higher power threshold value than that in other locations, indicating that the dynamic transmission’s obvious effect. So the rock foundation could be looked as the dominant transfer path for the vibration of the auxiliary powerhouse, especially for the hydraulic excitations originated from the spiral case and draft tube.

6. Conclusions
The dominant transfer path identification analysis with FEM power flow method would be very effective to the vibration diagnosis, reduction and isolation, especially for the complicated coupling dynamic system such as coupling vibration between the generator unit and the powerhouse structure.

For the hydraulic excited vertical vibration of the unit pier structure, oriented from the pressure pulsations in the spiral case and turbine, the energy transmissibility of the shaft system is more effective than from the head cover, but the transfer efficiency of the head cover is also significant.

The slab vibration of the generator floor mainly came from the horizontal direction such as wall and wind cowling, and the vertical slab vibration could be reduced by the beams and columns.

As for the vibration of the auxiliary powerhouse structure, the filing material with low stiffness, such as the closed-cell foam, in the structural joint may be an effective isolation component to restrict the vibration transmission actively. The dominant transfer path from main powerhouse to the auxiliary hall is the rock foundation.

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References
[1] Ohashi H 1991 Vibration and oscillation of hydraulic machinery (Aldershot: Avebury Technical)
[2] Deklerk D and Rixen D 2010 Component transfer path analysis method with compensation for test bench dynamics Mech. Sys. & Sig. Proc. vol 24 pp 1693-1710
[3] Newland D E 1966 Calculation of power flow between coupled oscillations J. of Sound and Vib. vol 3 pp 262-276
[4] Wu Q Q et al 2017 A model establishment and numerical simulation of dynamic coupled hydraulic-mechanical-electric-structural system for hydropower station Nonlinear Dyn. vol 87 pp 459–474
[5] Renno J M and Mace B R 2013 Calculation of reflection and transmission coefficients of joints using a hybrid finite element wave and finite element approach J. Vib. Sound vol 332 pp 2149-2164
[6] Lase Y and M. N. Ichchou M N 1996 Energy flow analysis of bars and beams: theoretical formulations J. Sound Vib. vol 192 pp 281-305
[7] Janssens K et al 2010 A new transfer path analysis method based on parametric load models Mech. Sys. and Sig. Proc. vol 25 pp 1321-1338
[8] Zhi B P and Ma Z Y 2015 Disturbance analysis of hydropower station vertical vibration dynamic characteristics: the effect of dual disturbances Struc. Eng. and Mech. vol 53 pp 297-309
[9] Zhi B P and Ma Z Y 2012 Research on the hydraulic turbine vertical vibration power flow in the head cover system Proc. of the 26th IAHR Sym. on Hydr. Mach. and Sys. (Beijing: China)