Recent Analysis Technologies for Hydropower Equipment

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1. Introduction

Computers are being used at each stage of hydropower equipment setup, from the receipt of a purchase order to onsite installation and testing.

The history of analysis technologies for hydropower equipment began with the introduction of flow analysis technology into runner design and has developed as computers have increased in speed and capacity. This analysis has made the transition from the classic performance improvement technique based on model tests using the try and cut method to computer-aided flow analysis and performance prediction technologies. Also, with the increase in the dimensions and head of hydraulic turbines, a strength and vibration analysis technique has been introduced. This technique contributes to the optimum construction design of hydraulic turbines. Presently, various numerical analysis technologies are used at each stage of hydraulic turbine planning and design.

This paper outlines the analysis technologies commonly used for hydropower equipment.

2. Flow Analysis Technologies

Flow analysis as a design tool for hydraulic turbines and reversible pump-turbines began in the 1960s with two-dimensional, inviscid flow analysis, and continued in the 1970s with quasi-three-dimensional analysis. The quasi-three-dimensional method divides a flow passage into many rotating flow surfaces of axial symmetry and performs iterative calculations, repeating the flow analysis for each flow surface and modifying the profile of the flow surface using each analysis result. Because this method requires only a comparatively small memory capacity and can be calculated quickly, it is still used as a simple design tool. However, this method is based on the approximation that fluid flows on a rotating flow surface having axial symmetry, and is insufficient to describe the details of much more complicated flows in actual hydraulic turbines and reversible pump-turbines. For example, it is known that flow over the pressure surface of high-specific-speed Francis runners used for low head projects is approximately perpendicular to the rotating flow surface, but this flow phenomenon can not be described by the quasi-three-dimensional method. In addition, because of recent demand for stable operation not only at the point of optimum efficiency and its vicinity but also over a wider range, the necessity to describe the internal flow at an operating point far from the design point has increased. The quasi-three-dimensional method has poor convergence in calculating these conditions, and little detailed information about the flow can be obtained from analysis with this method.

Using recently introduced three-dimensional viscous flow analysis technologies, complex flow phenomena in hydraulic turbines have become understood and the accuracy of analysis in regions far from the design point has greatly improved. Many flow phenomena are being clarified, such as the flow separation occurring in a runner during high-head and low-head operation or the channel vortex in partial load operation, the leakage flow from the blade tip clearance of a Kaplan turbine, and the reverse flow at the inlet of a reversible pump-turbine during high-head pumping operation. This progress in analysis technologies has made it possible to obtain more detailed information at the design stage than ever before.

On the other hand, the preparation of data for analysis and those analysis calculations require much more time than the previous quasi-three-dimensional analysis. Therefore, quasi-three-dimensional analysis and three-dimensional viscous flow analysis are properly used in combination at present.

The progress of flow analysis technologies has improved design accuracy and reliability. The previous method in which performance was improved by repeating model tests is gradually changing to a method in which the optimum design obtained from iterative flow analyses and then confirmed with a model. However, to completely eliminate model tests, strict direct numerical simulation of Navier-Stokes equations must be easily performed on desktop computers and the accuracy and reliability of these results must be recognized generally. These expectations are unrealistic at the present time. It should be noted that the model test is an effective method to verify the result of analysis. The flow analysis technologies are powerful because they quantify elements previously dependent on the designer's perception and sense and promote progress in design technology. These analysis technologies will contribute to expanding the stable operation region of hydropower equipment by shifting the range of instability or by controlling the strength of that phenomenon.

3. Strength Analysis Technologies

As described above, with the increase of computer speed and capacity, the finite element method (FEM) which had been previously impractical because of its enormous quantities of calculations became calculable in two-dimensions beginning from approximately 1970 and in three-dimensions from the mid 1970s. This technique also was applied to strength analysis of the main structures of hydraulic turbines and reversible pump-turbines. First, it was mainly used for structures having two-dimensions or axial symmetry with simple shell elements and beam elements, and then gradually became used in complicated, large-scale analyses with three-dimensional solid elements. It has been applied not only to simple supports or immovable restraints but also to constraint conditions closer to actuality, such as multipoint constraint. Recently, FEM analysis has been easily performed with desktop engineering workstations or personal computers. Static and dynamic stress and displacement are more precisely calculated, greatly contributing to improved equipment reliability, including fatigue strength.

It is important that each part of a high-head hydraulic turbine or reversible pump-turbine has the necessary stiffness to endure high water pressure. The FEM also handles nonlinear phenomenon such as the rapid increase in bolt tensility caused by opening a flange fastened by large bolts. In contrast, low-head bulb turbines have a large thin plate structure and it is important to predict the precise amount of deformation under manufacture, assembly, and installation. Our method of onsite installation is based on the result of analyzing deformation during operation.

4. Vibration Analysis Technologies

Eigenvalue analysis with FEM is generally performed to eliminate resonance problems.

Reversible pump-turbines often have a high head and large capacity to improve economical efficiency. They also require high reliability. Because a high head increases the exciting force of water pressure on the parts, an analysis of vibration in the water is necessary for the runner. A fluid reaction force proportional to the acceleration of vibration acts on the runner in the water and exerts the effect of additional mass, which lowers the natural frequency. The runner is also influenced by the stationary head cover and bottom cover. Therefore, it is necessary to perform fluid-structure-coupled vibration analysis that includes fluid around the runner and the stationary parts, and to ensure that the frequency of fluctuating stress is sufficiently far away from the resonance frequency. At present, verification is carried out both through analysis with software and the measurement of fluctuating stress at an actual head testing facility.

On the other hand, low-head bulb turbines have low stiffness and their natural frequency is low. Therefore, eigenvalue analysis is performed for the whole model.

A special example is the verification of the effectiveness of a pump-turbine structure for reducing building vibration. Vibration analysis of the building structure of a certain high-head, pumped-storage power station was performed. The analysis result agreed favorably with onsite measured values.

5. Transient Phenomenon Analysis Technologies

The analysis of transient phenomena in hydraulic turbines, especially the calculation of pressure rise (ΔP) and speed rise (ΔN) during load rejection, and the required flywheel effect (GD^2) that influence not only the preservation of the hydroelectric power plant building and equipment but are also directly related to the cost, is always carried out during estimation and planning stage. In other words, a method of closing guide vanes to minimize the required GD^2 while maintaining ΔP and ΔN within permissible tolerance is investigated. When a tailrace is formed by a long pressure tunnel, there is a possibility that pressure during load rejection will drop to the vapor pressure level (known as the water column separation phenomena) causing an abnormal pressure rise during the reattachment of water columns. Therefore, it is necessary to simulate water pressure behavior. In addition, analysis may be necessary in a complex waterway system such as where a penstock branch and a surge tank are combined to confirm stability of the governor control.

6. Conclusion

An outline of the history and recent analysis technologies of Fuji Electric's hydropower equipment has been presented. Other papers in this special issue introduce "Vibration Analysis Technologies for High Head Pump-Turbine Runners" and the "Application of Numerical Flow Analysis Technologies to Hydraulic Turbines and Pump-Turbines". We would be grateful if you would take the time to read them.