

Application of Numerical Flow Analysis Technologies to Hydraulic Turbines and Pump-Turbines

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1. Introduction

Numerical analysis technology has been widely developed as an important tool in engineering design due to the low cost and rapid development of Computer Technology (CT), especially in the Engineering Workstation (EWS) and Personal Computer (PC). In addition, the advancement of Computational Fluid Dynamics (CFD) technologies is also remarkable. A variety of new analytical techniques and turbulent flow models have been proposed and are now being applied to complicated flow analysis. Recently, several simulations with separation and swirl have been announced one after another, thereby expanding the range of application. Moreover, computer graphics (CG) technology has developed remarkably in recent years. This powerful drafting tool is used to visualize, in real time, analytical and data processing results on the computer display.

In this paper, the author introduces applications of the latest flow analysis technologies⁽¹⁾ to the design of hydraulic turbines and pump-turbines, and demonstrates the reliability and economy of the three-dimensional flow analysis technology.

2. Flow Analysis of Hydraulic Turbines and Pump-Turbines

2.1 Bulb turbines

A bulb turbine comprised of sixteen guide vanes and four runner blades is analyzed. The outline of the bulb turbine, which includes guide vanes, a runner and a draft tube, is shown in Fig. 1, and each operating condition is shown in Fig. 2. The optimum operating condition (on-cam) where cavitation at the runner entrance does not occur is made standard a point of computation (double circle). The computational domain extends from the inlet of the guide vanes to the draft tube exit, and the boundary conditions for the analysis include only discharge rate and head. To analyze the flow of this bulb turbine, two technologies are introduced.

2.1.1 Interaction between the rotor and stator

The guide vanes are stationary, and the runner

blades are rotating. In fact, the flow patterns are three-dimensional and unsteady flow. If the computations are carried out by full, three-dimensional, unsteady flow, a very large computer and calculation costs become necessary to analyze the interaction phenomenon of this unsteady flow. In order to avoid these problems, previous researchers divided the computational area. That is, rotating and stationary blades were independently calculated, the interface between rotor and stator was disregarded. However, it

Fig.1 Outline and computational results of the bulb turbine

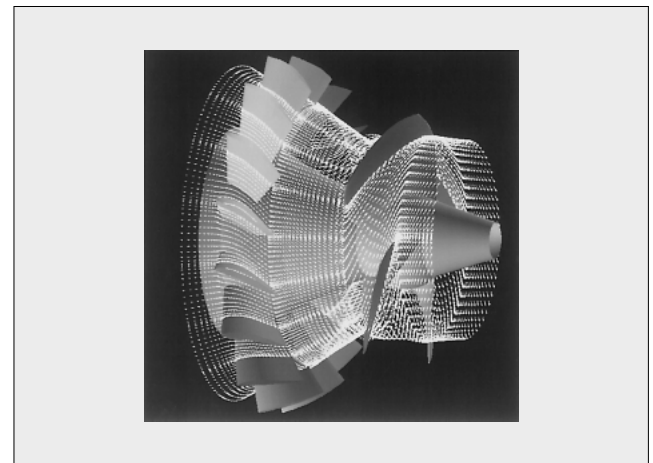
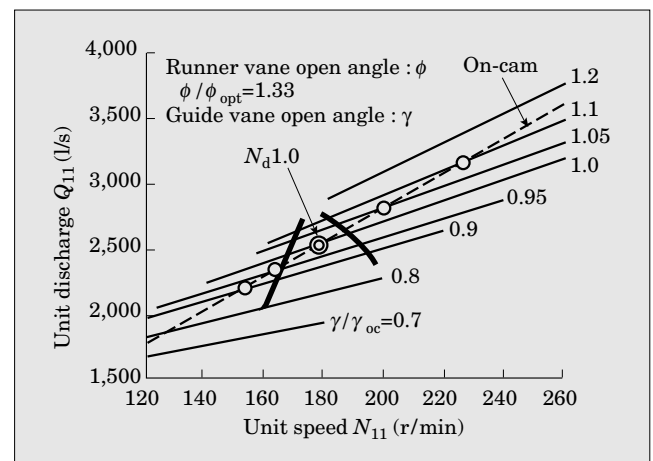


Fig.2 Discharge characteristics



was confirmed that this divided calculation was different from the actual flow⁽³⁾, and it was shown that the difference in the flow velocity distribution at the runner inlet was especially large. To evaluate the time average of a rotor-stator interaction correctly, the author proposed an approximate rotor-stator interaction analysis technique⁽²⁾. In this technique, the computational memory was decreased so that this computation could be carried out on a desktop EWS. Such techniques enable coupled analysis of the rotor-stator and use as a tool in hydraulic turbine design.

2.1.2 Leakage flow analysis technology

Leakage flow exists in the gap between the fixed discharge ring and rotating runner. When observing from the rotating runner, the leak flows from the pressure side of the blade tip gap toward the suction side. A local attack angle near the tip side at the leading edge is larger due to the effect of this leakage flow than in the case of disregarding the gap influence. The leakage flow from the blade tip gap strongly

Fig.3 Velocity and pressure distributions at the guide vanes' outlet

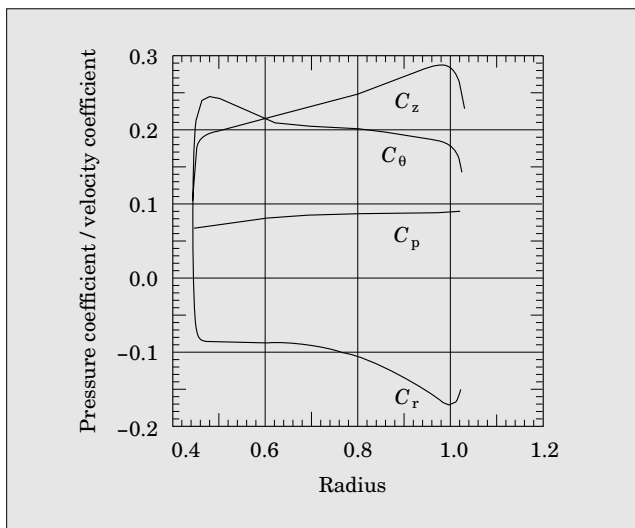
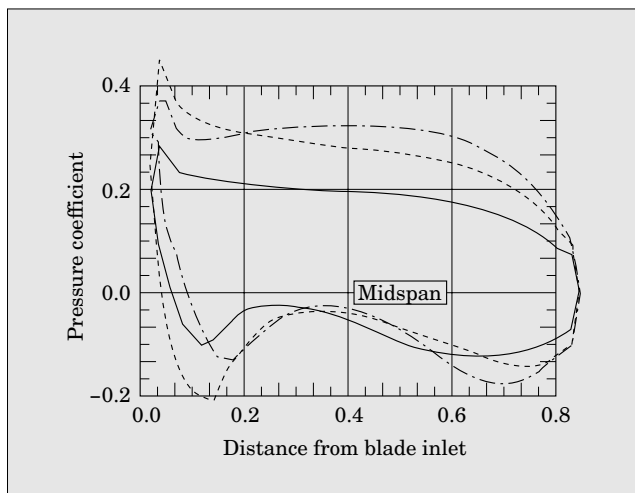


Fig.4 Pressure distribution on the bulb turbine runner



affects not only entrance cavitation performance but also downstream flow. Therefore, it is necessary to analyze the effects of leakage, taking the gap into consideration, to correctly evaluate the performance of the bulb turbine. As a result, the author developed the leakage flow analysis technique⁽²⁾ which enables the leakage analysis of a very small gap.

2.1.3 Computational results

Three-dimensional flow simulation in a bulb turbine can be accurately carried out by introduction of the flow analysis technologies described above. Figure 1 shows the analytical results of a bulb turbine which includes guide vanes, a runner and a draft tube in optimum operating condition. The length of vectors corresponds to the magnitude of flow velocity. Figure 3 shows the distribution of flow velocity and pressure at the guide vanes' exit. Here, the ordinate represents the velocity components (C_z , C_θ and C_r) in the axial, circumferential, and radial directions, respectively. They are normalized by the runner's peripheral speed, and the pressure coefficient C_p is normalized by the dynamic pressures of the runner's peripheral speed. The pressure distributions on the pressure and suction surfaces of the runner blade at midspan are shown in Fig. 4, with the three lines representing three on-cam

Fig.5 C_θ distribution by different passage forms upstream of the runner

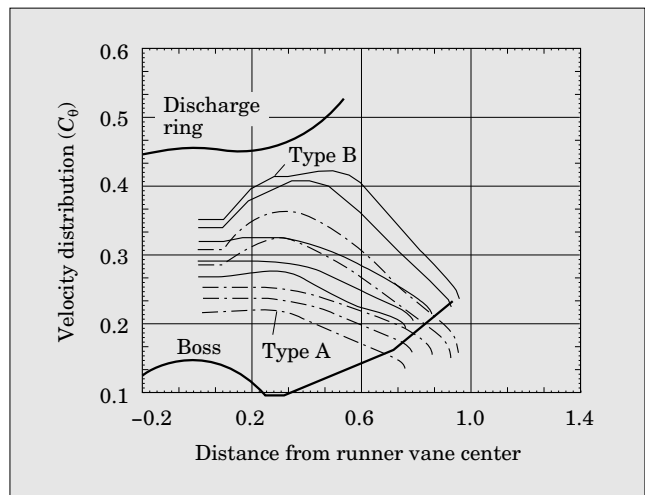
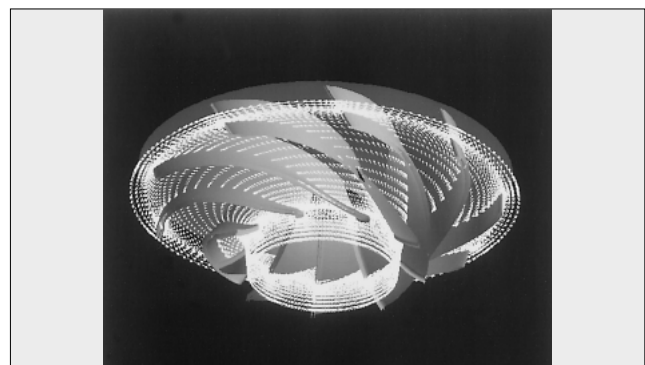


Fig.6 Outline and computational results of the pump-turbine



operating conditions.

In Fig. 5, the passage profile between the guide vane and runner is changed and then the distributions of circumferential velocity are compared from the boss to the discharge ring. It is understood that a difference exists in the absolute velocity and the spanwise spread of the velocity for both kinds of passages. The difference in velocity distribution directly affects the runner inlet flow condition. The best passage profile of such on-cam conditions can be chosen by flow analysis. These computational results will be very important in furthering runner design.

2.2 Pump-turbines

The pump-turbine operates the runner in either the forward or reverse direction and performs pump and turbine operations with one runner. Therefore, when the runner is designed, the performance of both pump and turbine operations must be considered. To improve the balance between pump and turbine perfor-

Fig.7 Velocity and pressure distributions at the inlet in low discharge pumping operation

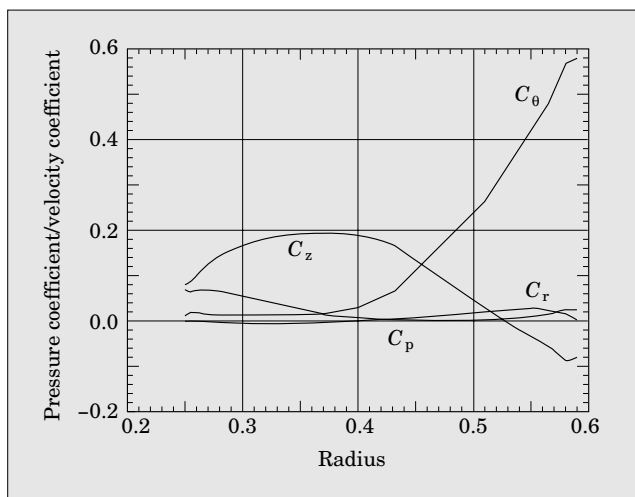
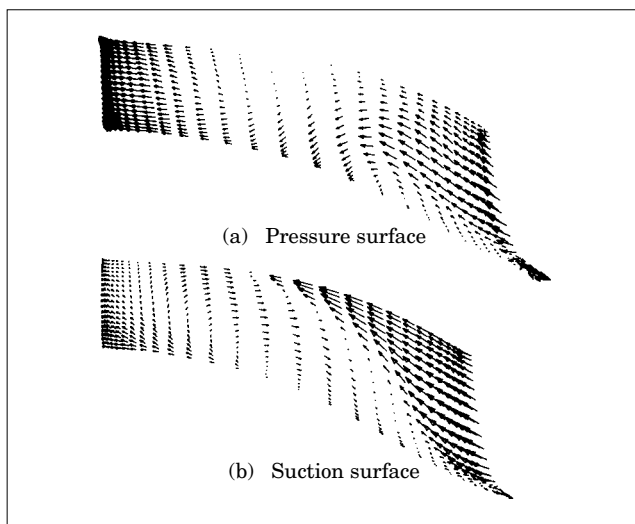


Fig.8 Velocity vectors at partial discharge



mance, analysis of the flow of the pump-turbine in the design stage is much more important than the ordinary turbine runner.

Figure 6 shows the flow field in the blade-to-blade passage at its most efficient pump operation. The reduction of radial velocity can be found on the pressure surface. When the discharge is decreased with the guide vanes having the same opening, reverse flows are created at the leading edge of the runner. Efficiency and head suddenly changes, and vibration

Fig.9 Computational results for the low-pressure range

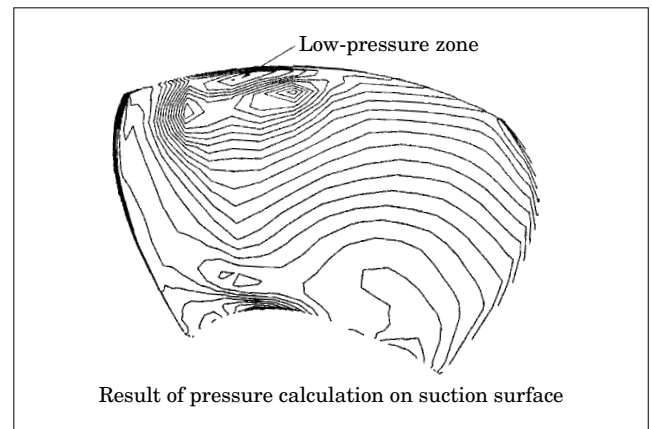


Fig.10 Erosion near the tip side on the suction surface of actual runner

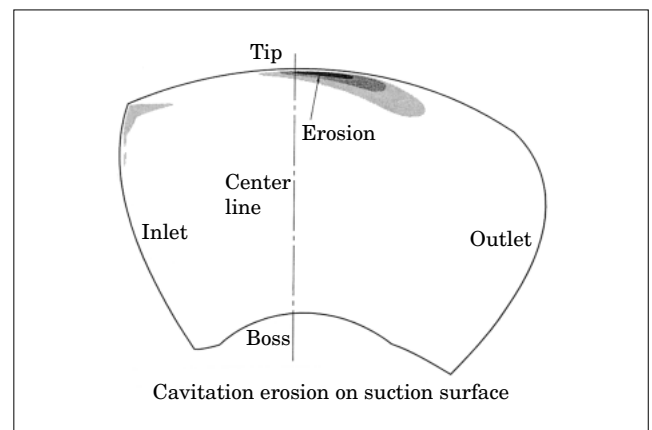
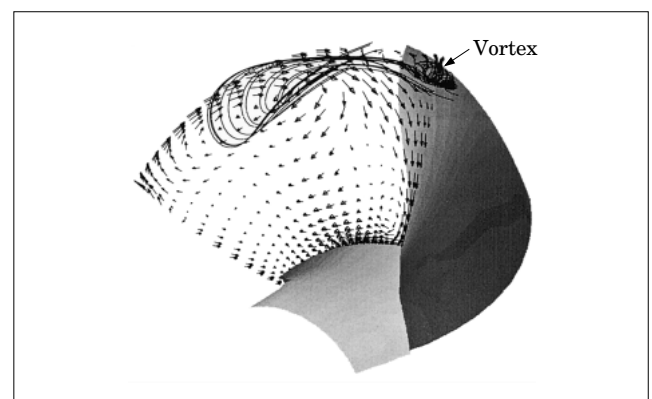


Fig.11 Tip leakage flow and vortex near tip side



and noise occur at the partial discharge operating conditions. Figure 7 shows the velocity and pressure distributions of the pump inlet in the case of reverse flow generating at the leading edge. The abscissa is the radius, the left side is the crown, and the right side is the band. Axial velocity C_z starts decreasing from midspan toward the band side and is negative near the band side. It is understood that C_θ increases steeply in the same area. It is possible to say that reverse flow occurs at the band side in this operating condition when such results are analyzed. Figure 8 shows the velocity vectors on the pressure and suction surfaces at this operating condition. A strong reverse flow is observed near the band side. Moreover, this reverse flow area expands from the pressure side toward the suction side. It can be confirmed that efficiency and head decrease due to reverse flow⁽³⁾.

The performance and appearance of the flow of the pump-turbine model in the initial design stage are obtained by computational results. From these results, the initial design can be evaluated, and any redesign for the next stage can be drawn. The accumulation of such analytical information and the improvement in both the analytical technologies and computational environments will contribute to building a more reliable tool for pump-turbine design.

2.3 Kaplan turbines

An existing Kaplan turbine runner to be replaced is also analyzed. The specific speed of this Kaplan turbine is $n_{SQ} = 156$ (r/min, m³/s, m) at the maximum efficiency point. As in bulb turbines, there exists the leakage flow through the gap along the blade outer periphery in Kaplan turbines. In high head machines, cavitation erosion can be generated due to this leakage. The Kaplan turbine mentioned in this paper was manufactured in the 1960's, with the discharge ring designed as a complete cylinder. Therefore, the gap expands at the leading and tailing edges by an increase in the runner opening. Figure 9 shows the pressure contours on the suction surface obtained by the analysis. A narrow, low-pressure area can be seen a little upstream of the runner's center line near the tip side, and a high-pressure range exists adjacent to this low-pressure range. Moreover, a low-pressure area is also found along the leading edge. In this turbine, extremely violent cavitation erosion was generated in the suction surface of the blade tip side, as shown in Fig. 10. In particular, the heaviest erosion occurs on the blade suction surface, where the gap is minimal in size. The dark color in this figure shows that erosion is heavy. Although the low-pressure range of the computational result appears a little upstream in comparison with the actual erosion, the shapes of the two results are very similar.

In Fig. 11, the flow field near the tip side on the suction surface is shown with the velocity vectors and streamlines. It is understood that a thin, strong tip

vortex is formed near the center of the runner where the gap is narrow. Moreover, the high-pressure belt observed in Fig. 9 is dependent on stagnant pressure. This in turn is a blade-to-blade secondary flow that collides with the blade suction surface at the inside of the tip vortex.

3. Conclusion

The development of three-dimensional analysis technologies and the computational results of the hydraulic turbines and pump-turbines are introduced. More detailed information regarding flow through the hydraulic turbine and pump-turbine can be obtained now than in the past by the advancement of the three-dimensional flow analysis technology. It is expected to achieve a wide but steady operating range by improving the efficiency of hydraulic turbines and pump-turbines.

However, the CFD technologies which have been developed are not perfect and have limitations in the field of numerical techniques and turbulent models. When commercial software is used, there are many instances where the computational results greatly differ from the actual flow in the case of complicated flow. Great care must be taken to recognize these occurrences. Therefore, the designer must perform flow analysis after fully understanding the suitable range of application for the computational code and the turbulent model. The hydraulic turbine's internal flow is a compound flow, as explained above, with separation, cavitation, and a strong vortex. Selection of the best computational techniques is necessary, in accordance with the various types and operating conditions of the hydraulic turbine.

As a quantitative design tool, the improvement of analysis technologies and the improvement of analytical accuracy and reliability is an important topic for the future. The mission of the design tool is to point the way for design improvement by analyzing performance defects of the hydraulic turbine. We intend to advance both utility and analytical technologies aiming at the achievement of the higher level CFD technology, by which the design can be completed through "Numeric experimentation" without relying on the model test.

References:

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