Characteristics analysis for different water heads on the efficiency hill chart of Francis turbine

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Abstract. Based on the test results of Francis turbine, the causes and inevitability of various hydraulic phenomena in the model combined characteristic curve for typical water heads were analyzed in this paper. The difference of the model combined characteristic curve from the low water head to the high water head is compared, and the characteristics and commonness of the model combined characteristic curve about different water head are summarized. Further, hydraulic performance and geometric features of Francis turbine are revealed by particularly analyzing model combined characteristic curves, and to provide powerful theoretical basis and definite modification direction for the hydraulic design of hydraulic turbine.

1. Introduction

The hydraulic turbine characteristic curve is used to express the energy conversion, cavitation and other aspects of the hydraulic performance, force properties and other properties at the different operating conditions, these properties is the external characteristic of the internal flow of turbine, known as the external characteristics of hydraulic turbine. The relationship between the parameters of turbine is complex, in order to determine the relationship between some parameters, taking the relationship between two parameters as a simple function though fixing some parameters, which was represented by a curve, this curve was called characteristic curve of hydraulic turbine, we call it the hydraulic turbine combined characteristic curve if the turbine performance curves plotted in a same graph[1, 2].

The main characteristics of the hydraulic turbine can express concentratively on the performance combined characteristic curves or model combined characteristic curve based on the head and flow coordinate or unit parameter coordinate. However, in order to represent the relationship between hydraulic characteristics and hydraulic turbine condition intelligibly, it's a common that applies the basic characteristic curve (equal efficiency curve, blade channel vortex curve, cavitation curve in the pressure and suction surface of the leading edge of the blade) and typical hydraulic phenomenon to describe the hydraulic characteristics of the turbine, such as the critical cavitation, incipient cavitation, Cavitation vortex and pressure fluctuation of typical position[3].

According to the external characteristic expression modes, characteristic curve of turbine can be divided into linear characteristic curve and combined performance curve. And the linear characteristic curve can be represented by operating characteristic curve, rotation speed characteristic curve and water head characteristics curves. (a) Operating characteristic curve is the curve drawn of turbine that
work at a fixed speed n and water head H; (b) Rotation speed characteristic curve shows the relationship among the turbine flow Q, output P and efficiency η and speed n when guide vane opening a₀ and head H is a constant;(c) Head curve indicates the relation curve about the output P, flow Q, efficiency η and head H when turbine guide vane opening a₀ and the speed n is a constant. The combined characteristic curve can be divided into the operating combined characteristic curves and model combined characteristic curve according to the prototype operation and model tests. (a) Operating combined characteristic curves uses the operation parameters of head H and output P or flow Q as the abscissa and ordinate, and to express the liner external characteristic curve of the prototype turbine; (b) Model combined characteristic curve uses the unit speed n₁₁ and unit flow Q₁₁ as the abscissa and ordinate to represent the liner external characteristic curve of the model turbine[4]. Pan xihe et al. [5] summarizes the existing study results towards pump turbine characteristic curves and divide the research results into two dimensional mathematical transformation and three dimensional curved surface fitting. Furthermore, a fitting method for pump characteristic curves of various geometries based on cubic uniform B spline is presented by Zhang lin et al.[6], and proves the method works well by building various pump test data.

In this paper, the typical model combined characteristic curves respectively were selected at the different water heads of 100 meters, 200 meters, 300 meters and 500 meters based on the test results and hydraulic design experience, meanwhile, a longitudinal comparison with the turbine equal efficiency curve, blade channel vortex curve, The cavitation curve in the pressure and suction surface of the leading edge of the blade, Cavitation vortex curve and the output restricted curve was conducted, and the characteristics and differences of hydraulic characteristic curve under different water head were analyzed and summarized, all above provide a powerful theoretical basis and definite direction of modification for the hydraulic design of the turbine.

2. Characteristic of the model combined characteristic curve

It’s the turbine model test that is considered still the final and indispensable verification means in hydraulic design of turbine, although the development of CFD technology has provided a new platform for the design of hydraulic turbine. In view of the model test, the model turbine will operate at the head region and output range that the prototype turbine may run, because of the long experiment period and expensive testing costs[7]. With the optimum operating points as the center, test conditions should cover the entire operation region as widely as possible. The final results of the model test of hydraulic turbine is the model combined characteristic curve, the comparison shows the model turbine hydraulic performances, and to provide references for selecting of prototype turbine. Figure 1 shows the Francis turbine model combined characteristic curves of four kinds of typical head respectively 100m, 200m, 300m and 500m, from which the similarities and differences can be seen.
2.1 Generality analyses of model combined characteristic curve

As shown in Figure 1, the Francis turbine model combined characteristic curve can be plotted when takes the unit speed $n_{11}$ and unit flow $Q_{11}$ as the abscissa and ordinate respectively and marks out the guide vane opening curves and equal efficiency curves at the entire test operating conditions. It can be scaled out the turbine pressure fluctuation isolines, cavitation inception contours and the critical cavitation coefficient curve at different measuring points. Within the test range, it appears a blade vortex inception curve and the development curve if takes the optimal region as central under the small opening and small flow; cavitation inception curves in the pressure surface of the blade inlet edge at high unit speed and large flow region and in the suction surface of the blade inlet edge at low unit speed and low flow region respectively; 95% output limiting curve and Cavitation vortex at the region of large opening and large flow. These curves are the inherent characteristics of Francis turbine; the boundary position can be adjusted in a small range, but cannot be eliminated.

2.2 Cavitation vortex and 95% output limiting curve

The output of Francis turbine increased with the increase of the guide vane opening, but the guide vane opening increases to a certain extent, the output will reach the limit value. Because the prototype turbine can normally achieve power adjustment in maximum output operation, the points of 95% limit output conditions at the same unit speed on the model combined characteristic curve, were connected to draw an output limiting curve. In general, the early hydraulic turbine is designed based on one dimensional or two dimensional flow theory, the manual drawing and semi-mechanization manufacture model turbine output characteristics is poor, it will soon reach the limit output if the guide vane turn around the optimal opening degree, therefore the selection of model turbine was restricted seriously as a result of the output limiting curve often appears in the test range. But now, with the help of powerful computer and CFD technology, in the hydraulic design phase, CFD numerical optimization has been carried out several times before model test. In addition, the advanced processing technology and CNC machining technology have been also applied. So the output limit of the model turbine has passed over far away from the optimum region and rarely appears in the test range.

Schematic diagram of the output limiting curve is given in Figure 1. In fact, as shown in the figure, the output limiting curves for four typical water heads in the model combined characteristic curve chart are appear in the test range.

2.3 Cavitation curve in the pressure and suction surface of the blade leading edge

The model combined characteristic curve of Francis turbine has a lot in common and its inevitability from the analysis of the model turbine hydraulic design. In general, on the combined characteristic
curve chart, the cavitation inception curve in the suction surface of blade inlet is more near the optimum region than the curve in the pressure side and the model selection for the low-head Francis turbine also greatly is limited by the cavitation inception curve in the suction surface of blade inlet. The general opinion is that, it is beneficial for the Francis turbine with slightly positive incidence angle at optimum operating condition to improve the prototype turbine efficiency at low head and rated operating point, accordingly, the stability and the weighted average efficiency could be improved at weight operation condition. The cavitation curve in the pressure and suction surface of the blade inlet is directly related to the runner inlet incidence angle, the cavitation inception in the suction surface of the blade inlet will appear rapidly from the optimum unit speed to the low unit speed on this chart. While the turbine turns from optimal unit speed to high unit speed, the blade leading edge pass zero incidence angle and then turned to negative incidence angle, having reached a certain intensity can appear the cavitation inception in the pressure side of the blade inlet, so it is far from the optimum operating region on the model combined characteristic curve chart.

In some model test institutions, the cavitation inception curve in the pressure and suction surface of the blade inlet and the blade channel curve were accustomed to be connected. Due to the blade channel vortex and cavitation phenomenon belong to observation experiment, it's difficult to identify substantially because of large differences of subjective factors at the operating condition conjunction of the blade channel vortex and the cavitation of the blade inlet.

For the Francis turbine at different water head range, the cavitation inception in the pressure and suction surface of the blade inlet is remarkable difference. In general, for the middle-low water head Francis turbine, the cavitation inception curve in the pressure and suction surface of the blade inlet will appear on the model combined characteristic curve chart because its operating region unit speed is large span. In addition no far away between the cavitation incipient and high head operating region, even it is difficult to eliminate the cavitation incipient curve outside of operation region for the low-head Francis turbine, as shown in figure 1(a). While operating at the high or super high water head, there is few cavitation incipient on the model combined characteristic curve owing to the narrow operation unit speed range and small speed test span.

2.4 blade channel vortex inception and development curve
According to the model test of hydraulic turbine, it is defined as the blade channel vortex inception if the vortex appears simultaneously in three blade channels of the Francis turbine runner, while all channels appear eddy is defined as the blade channel vortex development. In general, the blade channel vortex inception curve and its developing curve will appears in the experimental working condition region, they are parallel from high unit speed to low unit speed inclined down at low flow condition. In comparison, the blade channel vortex of the low water head turbine closes to the optimum region, and the one of the high water head turbine is far away from the optimal region. Many experimental curves showed that, the blade channel vortex of the low head model runner appears in the vicinity of output 60%Pr, and the one of the medium-higher water head runner occurs in the vicinity of output 45%Pr, and it is difficult to exclude it completely outside the stability operation region. The blade channel vortex of the high and super high water head turbine occurs in minimum flow rate condition, eliminated far from the outside output 45%Pr.

2.5 isoefficiency curve
Theoretically, there are two characterization curves to express the operation state of the runner on the model combined characteristic curve chart of the Francis turbine: zero incidence angle (Δβ=0) curve and zero circulation (Vv=0) curve. The two curves are orthogonal and are interacted and mutually restricted, which play a controlling role for the trend and gradient of the model efficiency curve trend and gradient. The equivalent efficiency ring on the model combined characteristic curve chart is affected by the interaction between the inlet incidence angle Δβ and the outlet circulation Vv of the runner.

For the iso-efficiency curves on the model characteristic curve chart of the different water heads,
their shape and efficiency gradient in all directions shows typical common and obvious difference. It generally believed that the turbine energy performance is the best when the runner operation at zero incidence angle and zero outlet circulation or slightly positive outlet circulation or alternating outlet circulation, therefore, the slope of the iso-efficiency curve is significantly smaller at the direction of curve $\Delta \beta = 0$ and $V_u = 0$ on the model characteristic curve chart. Normally, for a prototype turbine, its operation probability at the high water head condition is less than the one at the middle and low water head condition. A positive incidence angle at the blade inlet side is designed to improve the efficiency of a turbine under large opening, but the disadvantage is the rapid decline under small opening and low unit speed.

The guide vane and the draft tube play a decisive role in the overall shape of the efficiency curve on the model characteristic curve chart. For the runner, there are relatively good inflow conditions at zero incidence angle direction, but the hydraulic loss of tandem cascades will increase sharply with the guide vane opening decreasing. This means that the efficiency of the equal efficiency curve will drop sharply under small opening and high unit speed region. The outlet circulation of the runner has a great influence on the energy recovery of the draft tube, the best energy recovery performance of the draft tube will be achieved by the runner outlet with slightly positive circulation or alternating circulation, thereby, the high efficiency region of the turbine shows the characteristics of elliptical partial left distribution along zero outlet circulation curve.

The guide vane and draft tube play different roles for the turbine efficiency improvement in different water head range. For the high and super high water head Francis turbine, the guide vane opening is generally small and the flow velocity is great, so the hydraulic loss of tandem cascades is relatively large. This means that the optimum design of tandem cascades in the high and super high water head turbine is the most priority. For middle and low water head Francis turbine, the energy recovery of draft tube is a very significant. From the model characteristic combined curve perspective, the span of high efficiency curve ring is very large along zero outlet circulation direction. With the increase of water head and the reduction of optimum unit flow, the effects of draft tube gradually weakened and the impacts of tandem cascades are gradually increasing in the hydraulic turbine, the high efficiency curve circle varies from ellipse near zero circulation gradually to a circular by zero incidence angle control, as shown in Figure 1 (a) and (d). In addition, for middle and low water head Francis turbine, due to having the huge momentum in the turbine outlet, success or failure on hydraulic design of low water head draft tube has a significant effect on the low-frequency pressure fluctuation of the turbine.

### 3 Characteristics of pressure fluctuation in the different quadrants

It is generally known that hydraulic turbine pressure fluctuation is very complicated. Furthermore, the pressure fluctuation in different parts of the hydraulic turbine and different operating conditions shows different characteristics. According to the principle of hydraulic design, hydraulic characteristics of pressure fluctuation can be discriminated approximately in different quadrant in the model combined characteristic curve chart.

In general, the Francis turbine is designed according to the principle of no impact or somewhat positive incidence angle in the inlet and normal flow or somewhat positive circulation or alternating circulation in the outlet for the optimum condition. As shown in figure 2, the circumferential velocity component increases with the decrease of load, then a strong helical off-centered vortex rope appears in the draft tube. It brings out a low-frequency pressure fluctuation and cause the turbine units vibration.
In figure 2, the curve AB is the boundary curve of the turbine unstable operation caused by low frequency pressure fluctuation. At low water head and large flow region, negative incidence angle occurs in the runner inlet and flow separation appears on the blade pressure surface as well as cavitation. At this time, several vortex ropes show in the draft tube, which will affect seriously the turbine unit stability. The curve BC is taken as the region boundary curve, and the curve CD is the 95% output limiting curve. In the high load region, the negative circulation of the runner outlet causes the concentric vortex rope in the draft tube, and induces the vibration of the turbine unit, the curve DE is its boundary curve. In the high water head and low flow region, flow separation and cavitation will appear in the suction surface of the blade due to the existence of large positive incidence angle in the runner inlet. Meanwhile, the existence of the blade channel vortex will result in the medium high frequency pressure fluctuation and have an effect on the turbine unit stability even blade crack and the curve EA is used as the region boundary curve. The region surrounded by the connecting curves of the point A, B, C, D, E and A is defined as the stable operation region of Francis turbine.

4 Selection of the prototype turbine

Type selection of prototype turbine is influenced by different characteristics of different water head model combined characteristic curve. Their respective selection area also shows distinguishing feature.

Firstly, for low water head hydraulic turbine, the hydraulic turbine customarily operates in a large range of water head variation, and its operating region in the model combined characteristic curve chart is in a wide span, so the type selection is limited by the cavitation inception curve of the pressure and suction surface of the blade inlet, especially the suction surface cavitation inception curve. While the type selection of the high and super high water head hydraulic turbine is rarely influenced by the cavitation inception curve. Secondly, the stability operating region in the model combined characteristic curve chart of the high and super high water head hydraulic turbine is much wider than that of low water head hydraulic turbine. So turbine load adjusting range varies from 45%Pr~100%Pr for the high and super high water head turbine, while load adjusting range for the low water head turbine should be limited within 60%Pr. Thirdly, at low flow condition, low-frequency pressure fluctuation is caused by the draft tube vortex rope, so the steady operation output range of the prototype turbine is not lower than 40%Pr.

5 Hydraulic characteristics of hydraulic turbine
For the low water head Francis turbine (about 100 meters design water head), upper part load pressure fluctuation occurs frequently and is difficult to eliminate in model test, moreover, the more and more difficult to remove it with design water head decreasing. Considering large unit discharge and cavitation coefficient, it needs a larger suction height while low water head Francis turbine operating without cavitation. It is difficult to exclude blade channel vortex below 60% rated output as a result of unit water head containing relatively less energy. The cavitation curve of the suction surface of the blade inlet may enter the turbine operation area when water head variation of prototype turbine is large. The amplitude of the low frequency pressure fluctuation is comparatively fairly high, more than 8% peak to peak value generally.

For the medium and high water head Francis turbine (about 200 meters design water head), its specific speed value range is most suitable to design super giant hydraulic turbine, for instance, the runner diameter of 1000MW Francis turbine in Baihetan Hydropower Plant is about 8.5 meters, while the runner diameter of Three George’s 750MW turbine reaches to 10 meters. The blade channel vortex and cavitation curve in the suction surface of the blade inlet can be excluded outside the turbine stability operation region, however, exiting a certain difficulty about hydraulic design. A high suction height and deeper excavation depth is a requirement for turbine operating without cavitation. And the peak to peak value of low frequency pressure fluctuation is below 5%.

For the high and super high water head Francis turbine (above 300 meters design water head), the essential consideration of hydraulic and structural design is silt abrasion problem owing to high flow velocity passing turbine channel. The blade channel vortex and cavitation curve in the pressure and suction surface of blade inlet is far away from turbine stability operation area. For the runner with diameter $D_1 = 1~4$ meters, its manufacturing and repairing is very difficult and complex as a result of high synchronous speed, small runner size and more blades, especially is difficult to be welded at the crow and band of the blade midsection, where the number of blade is 17, even 32 splitter blades. Due to small turbine critical cavitation coefficient and cavitation inception coefficient, the higher turbine design water head, the lower its suction height.

6 Conclusions
The model combined characteristic curve can comprehensively reflect hydraulic performance of model hydraulic turbine. The similarities and differences of each model turbine can be explored by detailed analysis of model combined characteristic curve in different water head range. And it can further reveal the curve’s change regulation and guide hydraulic design engineers to carry out turbine performance optimization.

Acknowledgement
The research was supported by The National Natural Science Foundation of China (51479166) and the Specialized Research Fund for the Doctoral Program of Higher Education of China (20126118130002).

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