Study on the Pressure Pulsation inside Runner with Splitter Blades in Ultra-High Head Turbine

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Abstract: Runners with splitter blades were used widely for the high efficiency and stability. In this paper, the unsteady simulation of an ultra-high head turbine at the best efficiency point, 50% and 75% discharge points were established, to analyze the pressure pulsation in the vaneless space, rotating domain and the draft tube. First of all, runners with different length splitter blades and without splitter blades were compared to learn the efficiency and the pressure distribution on the blade surface. And then the amplitude of the pressure pulsation was analysed. The peak efficiency of the runner with splitter blades is remarkably higher than that of the corresponding impeller without splitter blades. And the efficiency of the turbine is the highest when the length ratio of the splitter blades is 0.75 times the main blades. The pressure pulsation characteristics were also influenced, because the amplitudes of the pulsation induced by the RSI phenomenon were changed as a result of more blades. At last, the best design plan of the length of the splitter blades (length ratio=0.825) was obtained, which improved the pressure pulsation characteristics without significant prejudice to the efficiency.

1. Introduction
There are abundant hydraulic power resources in the southwest China, however this area is also famous for the precipitous, so the water head of most the planning power plants are higher than 200 meters as a result of the complex topography. Furthermore, 70~80% of the top 10 annual generation capacity power plants have a water had between 300m and 800m, and the total generation capacity of them will exceed 400 billion kWh¹.

In the past, Pelton turbines was employed in such ultra-high head power plants, but with development of high head Francis turbines technology, Francis turbines with splitter blades gradually get more chances because of its low specific speed, high efficiency, light weight and low construction cost. Runners with splitter blades can effectively decrease the secondary flow loss, improve load distribution...
of blades, extend the high efficiency region, decrease pressure pulsation and improve the cavitation characteristics when comparing with traditional runners [2].

Splitter blades technique is now one of the techniques frequently used in the design and application of turbo-machinery, a lot of researchers have done great job in studying the influence of splitter blades to pumps [3-10] and fans [11]. However, there was little research on the splitter blades of turbines. A few researchers such as M. Harano [12], and so on [13-15] had simulated the flow field of turbine with splitters blades. Hou Li hua [16] analyzed the influence of the length of the splitter blades to the physical characteristics and the cavitation characteristics of the turbine, however the influence of the length of the splitter blades to the pressure pulsation is not analyzed.

It is important for the ultra-high head turbines to reduce the fatigue stress of the blades and improve the stability of the power plant. In this paper, the flow characteristics of the turbine with splitter blades were analyzed. Firstly, the effects of the length of the splitter blades on the flow field and the output characteristic at different flux were studied, and the flow fields of runners with and without splitter blades were also compared. Then the analysis of the effects of the splitter blades length on the pressure pulsation inside the flow domain is proposed.

2. Computation model and mesh
The simulation domain includes the entire Francis turbine model flow passage, and the model has a 0.624 m diameter runner with 16 main blades and 16 splitter blades, as shown in figure 1. The number of stay vane and guide vane are both 24, and a structured grid is used for the guide vane. Other parts of the flow domain used unstructured gird. In order to get the most economical number of grid for this model, grid convergence study was made, and the final mesh has 756 609 nodes and 2 317 980 elements.

The simulations contain both steady and unsteady simulation. The steady simulation used SST model because of its agreement with testing results on external characteristic. In the unsteady flow calculation, the unsteady second order implicit formulation is used for time discretization, the finite volume algorithm is used for the space discretization. Several time steps (1/60T, 1/80T, 1/100T and 1/120T) have been tested contrastively for one condition, and the time step of 1/100T is found to give similar results with 1/80T and 1/120T, then this time step is selected for all calculation conditions. The total calculation time for each calculation condition is about 15T (T is one revolution time), and the convergence precision standard is set to $10^{-4}$.

Monitors inside the flow passage are shown in figure 2, and the monitor points were named according to the position.

![Figure 1. The calculation model](image1)

![Figure 2. The monitor points inside the flow domain](image2)
3. Calculation result and analysis

3.1 Steady calculation result and analysis

Figure 3 is the schematic diagram of the parameter will be used in this paper to describe the splitter blades. The length of the splitter blades will be described as the length ratio, which means the fraction of the main blade’s meridional length where the trailing edge of the splitter blade ended. The location of the splitter blades is described with parameter A, which means the fraction of the distance between the splitter blade and the upper main blade with the distance between two main blades.

Figure 4 is the hydraulic efficiency of the runners with different length splitter blades under three working points. While the length ratio of 0 means there are no splitter blades. \( Q_{\text{bep}} \) means the best efficiency point, and other two working points are the points where the discharge of the turbine is 75% and 50% of the discharge of the best efficiency point. It can be seen that the efficiency of the turbine is higher when there are splitter blades, because the splitter blades help to uniform the inlet flow of the runner and decrease the secondary flow loss, the total flow loss in the runner is decreased. In consideration of efficiency, the best length ratio is in the range from 0.675 to 0.75. In the best efficiency point, the best length ratio is 0.75, while the best length ratio of 75% \( Q_{\text{bep}} \) and 50% \( Q_{\text{bep}} \) are 0.825 and 0.9 respectively. The result is not in good accordance with the tendency predicted by Yihua Hou\(^{[16]}\), especially in the small discharge point, the efficiency is not dropped when the length ratio exceeded 0.85, the difference may be caused by the design of the blade and the specific speed of the turbine. When the specific speed is smaller, the angle of the guide vanes will not change a large angle when increase or decrease the discharge in a large scale, as a result the inflow angle will just change in a small range, thus the flow situation keeps stable.

![Figure 3. The definition of the length ratio and the location of the splitter blades](image)

![Figure 4. The hydraulic efficiency of the runners with different length splitter blades](image)

It can be seen from figure 4 that the efficiency increased sharply when splitter blades were added. The pressure distribution on the surface of the blades is shown in table 1. In table 1, when length ratio equals to 0, which means that there is no splitter blades in the runner, the pressure distribution is non-uniform. And when the length ratio is 0.45, the pressure distribution on the surface of the splitter blade is uniform along the flow routine, the pressure distribution on the main blades begin to be more uniform from the middle of the blade, where the span is 0.5. While the length ratio is 0.525, the pressure distribution on
the blade from the middle (span=0.5) to near the shroud (span=0.9) all become better. As the length ratio goes up to 0.6, the pressure distribution on the whole working surface of the blades becomes uniform. And this situation continues as the length ratio is in the range of 0.675 and 0.825, in this range, the pressure distribution is quite good, that is the reason why in this length ratio the efficiency is the highest. However, when the length ratio is 0.9, the distribution is not as uniform, the flow in the runner is not that smooth, and the flow loss goes up, as a result, the efficiency begins to drop.

Even though the length of the splitter blades varies a lot, the discharge of the runners is quite stable, the fluctuation of the mass flow rate remains below 0.2%. Since the length ratio is below 1, the outlet square of the blades area is not influenced by the splitter blades. This means the splitter blades help to uniform the flow and improve the efficiency without affecting the discharge and the power of the runner. So in consideration of efficiency and discharge, the best choice of the length ratio of the splitter blades for this runner is 0.75. But the unsteady flow characteristics should be took into consideration, which will be analyzed in the following.

**Table 1.** Pressure distribution on the working surface of the blades with different length ratio

| Length ratio | 0    | 0.45 | 0.525 | 0.6  | 0.675 | 0.75 | 0.825 | 0.9  |
|--------------|------|------|-------|------|-------|------|-------|------|
|              | 75%  | 50%  | 75%   | 50%  | 75%   | 50%  | 75%   | 50%  |
| Q_bep        | 5.32 | 4.74 | 4.16  | 3.57 | 2.99  | 2.41 | 1.82  | 65.64| 72.72 |
|                | 5.11 | 5.19 | 5.04  | 4.90 | 4.79  | 4.69 | 4.64  | 4.54 |

As predicted, the best location of the splitter blades is the middle (A=50%) of the two main blades, but the inside flow characteristics of A=40% and A=60% condition need to be analyzed to get a better understanding of the effect of the splitter blades.

Table 2 is the relationship between the hydraulic efficiency with the location and the length of the splitter blades. It can be seen from the table that the efficiency is lower when the splitter blades are not located in the middle of two main blades, but the efficiency of the runners with A=0.6 is higher than that of runners with A=0.4.

**Table 2.** The hydraulic efficiency of the runners with splitter blades in different location and with different length ratio

| A   | Length ratio= 0.75 |     | Length ratio= 0.675 |     | Length ratio= 0.6  |     |
|-----|--------------------|-----|--------------------|-----|--------------------|-----|
|     | Q_bep  | 75% | Q_bep  | 75% | Q_bep  | 75% |
| 0.6 | 95.75  | 60.93| 95.75  | 60.93| 95.75  | 60.93|
| 0.5 | 95.81  | 60.93| 95.81  | 60.93| 95.81  | 60.93|
| 0.4 | 95.74  | 60.93| 95.74  | 60.93| 95.74  | 60.93|

The velocity vector along the blade surface is shown in figure 5, it can be seen that the location of the splitter blades will affect the flow inside the runner, when the splitter blade is located nearer to the suction side of the main blade (A=0.6), the flow will squeeze near the suction side of the blade since the
flow area is smaller and conversely will become loose in the working side of the blade since the flow area is larger, as a result, the pressure of the working side of the blade will increase, and the pressure of the working side of the blade will decrease. This will lead the result of increasing pressure difference, which will cause a higher efficiency of the runner.

![Figure 5. The velocity vector along the blade surface under 50% $Q_{bep}$](image)

(a) $A=0.6$  
(b) $A=0.5$  
(c) $A=0.4$

3.2 Unsteady calculation result and analysis

As mentioned before, severe monitor points were set inside the fluid domain, such as points near the blade surface along different span ratio (span=0.1, 0.5 and 0.9) and at different streamwise location, the trailing edge of the guide vanes and the inlet part and elbow part of the draft tube. Now the pressure pulsation of the monitored points will be analyzed under 50% $Q_{bep}$.

When the length ratio of the splitter blades increased from 0 to 0.9, the trends of the pressure pulsation of different area inside the flow passage are different. As shown in figure 6 (a), the first order frequency of the monitor in the outlet of the guide vane area is 16 times the rotation frequency, and there are also other frequencies, among them, the highest amplitude one is the frequency of 32 times the rotation frequency. This phenomenon is easy to understand, since there are 16 main blades and 16 splitter blades (when the length ratio is 0, there is no splitter blades). As the length of the splitter blades increases, the amplitude of the frequency of 32 times the rotation frequency is higher, and the amplitude of the frequency of 16 times the rotation frequency is higher. And when the length ratio is 0.75 and 0.825, the amplitude of all the frequencies is lower.

Figure 6 (b) is the frequency domain of the monitor near the pressure side of the blade surface (span ratio=0.9, streamwise ratio=0.75), the main frequency is 24 times the rotation frequency, as a result of 24 guide vanes. The amplitude of the frequency is the lowest when the length ratio is 0.9.

Figure 6 (c) is the frequency domain of the monitor in the inlet area of the draft tube, there are a lot of frequencies in the frequency domain, and when the length ratio is 0.825 and 0.9, the amplitude of all the frequencies is the lowest.

As a summary, when the length ratio is 0.825, the amplitude of the pressure pulsation in the whole flow passage is the smallest.
4 Conclusions
In this paper, SST $k-\omega$ model have been applied to the steady and unsteady numerical simulation for 3D flow in whole flow passage of an ultra-high head Francis turbine with splitter blades. The effect of the length of the splitter blades both to the efficiency and the pressure pulsation characteristics were analyzed. The analysis of the results shows the following conclusions:

(1) The peak efficiency of the runner with splitter blades is remarkably higher than that of the corresponding impeller without splitter blades. And the splitter blades hardly affect the discharge of the turbine.

(2) The efficiency of the turbine is the highest when the length ratio of the splitter blades is 0.75 times the main blades. When consider the part discharge working conditions, the length ratio of 0.825 and 0.90 turned out to be good for the promotion of the efficiency at 75% $Q_{bep}$ and 50% $Q_{bep}$ respectively.

(3) When the length ratio is 0.825, the amplitude of the pressure pulsation in the whole flow passage is the smallest. It is important for the ultra-high head turbines to reduce the fatigue stress of the blades and improve the stability of the power plant. So length ratio= 0.825 is the best choice for this turbine to obtain both high efficiency and good stability.

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