Effect of Leading Edge Profile on Cavitation Performance of Mixed Flow Impeller

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Abstract. Cavitation inception on a pump impeller blade is affected by the blade profile around the leading edge. Even if the difference of the blade profile is limited around the local leading edge area, such as, different elliptical ratios of the leading edge, pressure limitation of cavitation inception differs drastically. This leads to the difference of cavitation erosion speed, and it is important to understand the mechanism and quantitative effect of leading edge shape on cavitation inception, to avoid troubles related to cavitation erosion. In this study, CFD and experimental investigation were carried out to clarify the effect of leading edge shape on cavitation inception. The tested pump was a mixed flow pump, which is widely used as a circulating water pump for power plants. Various leading edge shape were calculated and tested with keeping the blade camber line. Only elliptical ratio of the leading edge on the suction side was changed. As for CFD, isolated impeller, single phase analysis was carried out for 90, 100 and 110\% design flow rates, blade surface area on which pressure is less than the vapour pressure was evaluated for each cases. In the experiment, 5 bladed mixed flow pump model was used, and the cavitation length was measured. Both experimental and calculated results were compared and considered. As a result, it was clarified that the optimized value of elliptical ratio is around 2 to 6, which changes depending on the flow rate. Additionally, when the elliptical ratio is 4, was almost half of the one with elliptical ratio 1. Cavity length and cavitation intensity has positive correlation, and estimated erosion speed when the elliptical ratio is 4 is almost an eighth of baseline.

1. Introduction

Many industrial pumps are operated under cavitating condition, therefore, various kind of cavitation researches has been conducted. It is well known that one of the key factors for cavitation is the design of leading edge, such as, incidence angle, slant or blunt, swept back, etc. One of the classic paper to clarify the relationship between the cavitation performance and the leading edge was done by Moore, et.al. [1], they tested inducers with liquid hydrogen. Three types of leading edge was tested, slant, blunt, and its combination. They found that the blunt leading edge case showed the greatest thermodynamic effect of cavitation. Another study was done by Tao, et.al. [2], they tried to modify cavitation performance of pump turbine in pumping mode, by applying blunt leading edge. Similar investigation was done by them, for centrifugal pump impeller [3]. Blume, et.al., investigated the cavitation performance of circular leading edge blade, by comparing detailed measurement and numerical approach [4], and similar kind of investigation had been done by many researchers [5] [6] [7]. From these researches, it can be judged that the leading edge shape highly affects the cavitation performance and its dynamics, therefore, leading edge shape should be specially cared for the purpose of preventing several types of cavitation related troubles, like surge, noise, vibration, and erosion.
However, usually it is quite difficult to precisely control the leading edge shape of the impeller for industrial pumps, because, the cost for check and control the leading edge shape (Initial cost) is comparable or more expensive than blade modification cost after erosion is found (Maintenance cost). To reduce both initial and maintenance cost, it is necessary to consider a simple evaluation method for cavitation erosion, and clarify the tolerance of the blade geometry.

Turbomachinery Society Japan, hereinafter, “TSJ”, collected many erosion cases, and published as a standard about cavitation erosion [8]. In this standard, they summarized the cavitation erosion rate with several empirical formula, in a viewpoint of practical use. One of them is the relationship between erosion rate and cavitation length. Recently, this standard is often referred in Japan to design the industrial pumps.

The final goal is to provide a solution to avoid cavitation erosion with minimum costs. Based on the idea that the erosion rate can be evaluated by the cavitation length, main purpose of this study is to clarify the relationship between the cavitation length and the leading edge shape, by both experimental and analytical approaches.

2. CFD evaluation

2.1. Analysis method

Figure 1 shows the schematic shape of the leading edge of a mixed flow pump impeller. As shown in the figure, the leading edge shape of the blade suction surface is modified, while the pressure surface is maintained. If the pressure surface is modified, the throat area increases, and reduces the pump performance, especially at the best efficiency point. The baseline shape has a simple circle cross section, leading edge radius is half of the blade thickness. Suction surface profiles of modified cases are elliptical, with various elliptical ratio from 0.5 to 6.0.

The target pump is 5 bladed mixed flow impeller, its specific speed is about 1000 [m, rpm, m³/min], as shown in figure 2. The model impeller diameter is 266mm, operated in 1,500 rpm. The impeller isolated calculation was done by changing flow rate and leading edge shape. To simplify the problem, analysis was performed for a single blade with periodic boundary conditions, steady state, and single phase.

![Figure 1](image_url)  
**Figure 1.** Schematic shape of leading edge. Only the suction surface (bottom side of this figure) is modified in this study, to maintain the pump performance.
Figure 2. Computational domain of mixed flow impeller.

Table 1. Pressure criteria for several NPSH conditions

| NPSH [m] | Cavitation coefficient $\sigma$ [-] | Pressure criteria [m] |
|----------|-----------------------------------|-----------------------|
| 9.16     | 0.200                             | 0.238                 |
| 7.83     | 0.170                             | 1.577                 |
| 6.49     | 0.140                             | 2.916                 |
| 5.15     | 0.110                             | 4.255                 |

To evaluate the cavitation performance from single phase analysis, the simplified idea of “virtual cavitation area” is introduced in this study. The “virtual cavitation area” equals to the blade surface area of its surface pressure is below than the vapour pressure. To consider about the cavitation, volume of the pressure less than the vapour point is more accurate. However, sheet cavitation is usually dominant in circulating water pump, it is not necessary to evaluate the volume, and to easily compare with experimental results, virtual cavitation area is used for evaluating cavitation length in this study.

As for the boundary conditions, constant total pressure and flow rate were applied for both the inlet and outlet boundary, respectively. The prescribed total pressure at inlet is 9.16 m, this is equivalent to the condition of cavitation coefficient $\sigma=0.2$. And vapour pressure at 20 degrees Celsius is 0.238 m. In this study, the cavitation coefficient $\sigma$ is defined by NPSH normalized by the fluid density and second power of peripheral velocity. Therefore, surface area where the pressure is less than 0.238 m, is the “virtual cavitation area”. To evaluate the lower NPSH condition, the virtual cavitation area can be evaluated just changing the pressure criteria, not changing the inlet total pressure, as shown in Table 1. It is not necessary to calculate with another inlet total pressure conditions.

2.2. Analysis results

Pictures of virtual cavitation area in the condition of 110%$Q$, at $\sigma=0.140$, are shown in figure 3. It can be seen that the area is affected by the Elliptic Ratio of leading edge (hereinafter, $ER$). To compare the tendency, the virtual cavitation areas for various cases are summarized in figure 4. In these figures, the virtual cavitation area for each cases are normalized by the 100%$Q$ case, $\sigma=0.140$ and $ER=1$. In some cases, the elliptical leading edge is effective to reduce the size of the virtual cavitation area, especially in case of higher flowrate, or higher cavitation coefficient $\sigma$. Its effect is maximized in case of $ER$ more than 4, however, it should be noted that the virtual cavitation area at 90%$Q$, $\sigma=0.110$ condition tends to increase when $ER=6.0$. From these facts, it can be estimated that optimum $ER$ to minimize the cavitation length could be around 2 to 4, from this CFD investigation.

This tendency can be seen from the cavitation inception coefficient, shown in figure 5. In this case, the cavitation inception coefficient is calculated from the minimum pressure on blade surface. It is clear to see that the cavitation inception of $ER=6$ is minimum at 110%$Q$ condition, however as decreasing the flowrate, it becomes larger compared with other cases. And the cavitation inception coefficient of $ER=2$, or 4 are relatively small for wide flow rate conditions.
Figure 3. Visualization of the “virtual cavitation area”, at 110%$Q$, $\sigma=0.140$. Virtual cavitation area changed depending on the Elliptic Ratio ($ER$) of leading edge.

Figure 4. Trend of the “virtual cavitation area” against flowrate, Elliptic Ratio $ER$, and cavitation coefficient $\sigma$. Virtual cavitation area for each cases are normalized by that of 100%$Q$, $\sigma=0.140$, $ER=1$. 
Figure 5. Cavitation inception coefficient, for various elliptical ratio of leading edge (ER)

3. Experimental evaluation

3.1. Experimental method

To confirm the analytical results, model test was carried out. The tested impeller is shown in figure 6. Leading edge profile on suction surface of each blade was modified as shown in the figure 7. In this test, \(ER=1.0\) (baseline), 2.0, 4.0, and 6.0 were tested at the same time.

Figure 6. Tested impeller
3.2. Experimental result

The cavitation inception coefficient for each blade was measured and summarized in figure 8. In terms of cavitation inception, it is clarified that $ER=4.0$ was the best for wide flow rate range. $ER=6.0$ was not bad, however, it decreases with the flow rate. Cavitation inception coefficient obtained by both CFD and experiment are compared in figure 9. Although the tendency is a bit different in case of $Q/Q_d=90\%$, however, it can be judged that the optimum $ER$ to minimize the cavitation inception coefficient is around 4, and between 2 to 6 is acceptable.

![Figure 7. Magnification of leading edge portion of the impeller](image)

![Figure 8. Experimentally measured cavitation inception coefficient $\sigma$](image)
Figure 9. Comparison of cavitation inception coefficient obtained by CFD and experiment.

Next, the cavitation area for each blade was evaluated as follows. At first, the instantaneous image of cavitation on each blade was recorded by camera with stroboscope, and the cavitating region was evaluated optically by binalizing the image. Samples of measured cavitation area are shown in figure 10.

Figure 10. Sample image of measured cavitation area.
Then, cavitation area projected on the blade is obtained with binarizing the image. To evaluate the cavitation erosion speed, the cavitation length for each condition is required (mentioned later, in detail). Then, the cavitation area was divided by the impeller blade span at the leading edge. From this, averaged cavitation length was obtained. The measured cavitation length for various cases are shown in figure 11, and in these figures, cavitation length are normalized by impeller diameter.

The cavitation length at $ER=4.0$ is the minimum for all conditions. The elliptic leading edge especially is quite effective for higher flow rate conditions, in cases of $\sigma=0.220$ and $0.180$, cavitation was not observed when the elliptical leading edge was applied. The elliptical leading edge of $ER=4.0$ can reduce the cavitation length about 20 to 50%, compared to the case with $ER=1.0$.

Finally, measured critical cavitation coefficient curve is shown in figure 12. In this figure, critical cavitation condition is defined by the 3% head drop condition. Please note that the leading edge of each vane has different $ER$ in this test, therefore, the test results show the averaged value of $ER>1.0$. Comparing with the case of $ER=1.0$, critical cavitation curve was changed slightly, however, remarkable differences comparable to the cavitation length (figure 11) were not observed. The is
explained by the elliptical leading edge affects on the local flow field, but in case of 3% head drop condition, cavitation is not a local phenomenon but extends to block the throat area. Therefore, it should be noted that elliptical leading edge can only modify the cavitation performance when the cavity is not extended to the throat region.

Figure 12. Critical cavitation coefficient curve. In case of ER>1.0, elliptical ratio of leading edge for each blade is different as stated in Figure 7.

4. Evaluation of cavitation erosion

Finally, to understand how the cavitation erosion is mitigated by elliptical leading edge, cavitation erosion rate is estimated in accordance with the TSJ standards [8]. Cavitation erosion rate is expressed as following equation.

\[
Erosion \ Rate = C_L \left( \frac{L_{cav}}{L_{cav,ref}} \right)^{2.83} \left( \frac{p_0 - p_v}{\frac{1}{2} \rho v^2} \right) \left( \frac{R_m^2 F_{mat}}{\alpha} \right)^{0.36} \]  

(1)

For about detailed expression of this equation, please refer to the standard [8]. In this case, only the cavity length is changed as applying the elliptical leading edge, therefore, normalized erosion rate can be expressed as follows. In this equation, erosion rate is normalized by that of baseline leading edge case.

\[
Normalized \ Erosion \ Rate = \left( \frac{L_{cav,ER=x}}{L_{cav,ER=1}} \right)^{2.83} \]  

(2)

That is, normalized erosion rate is proportional to the 2.83th power of the cavitation length ratio. This equation is plotted in figure 13. The elliptical leading edge can reduce the cavity length to 20 to 50% of the baseline. This means that it has the potential to reduce the cavitation erosion rate by 50% down to 13%.
5. Conclusion

In this study, the effect of leading edge profile on cavitation performance was evaluated by CFD and model test. As a result, it is clarified that the elliptical leading edge is effective to reduce the cavity length, and elliptical ratio 4 is optimum for wide range of flow rate. In case of applying the leading edge with elliptical ratio equals to 4, the cavity length can be shorter by about 20 to 50%. This will reduce the cavitation erosion rate by 50% down to 13%, according to the TSJ guideline.

Leading edge shape presented in this study is optimum to reduce the cavity length, but it should be noted that this is optimum when a pump is operated with enough suction pressure. Once the pump inlet pressure is decreased and the leading edge cavitation is fully developed, no remarkable difference can be observed even if the local leading edge shape is different. However, many of industrial pumps, such as circulating water pumps are operated moderate cavitating condition, therefore, it can be judged that the presented optimum range is effective to reduce the cavity length, and to prevent the cavitation erosion.

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