

Cavitation strengthening of curved blades with submerged waterjet: A preliminary experimental investigation

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Abstract. Cavitation strengthening is usually implemented on flat specimen surface and relevant conclusions are difficult to be extended to curved blades. In the present work, cavitation strengthening for the curved surface is treated. A systematic consideration covering primary factors behind cavitation strengthening is substantiated in curved impeller blades. The submerged waterjet is used to trigger cavitation and then the cavitation impact on the impeller blades is produced. Apart from the attempt to construct a cavitating waterjet rig for strengthening model blades, the approaches of evaluating cavitation strengthening intensity are presented as well. The correlation between the results obtained in both the laboratory level and practice is established. The possibility of implementing the strategies for industrial use is validated. It is anticipated to provide a reference for the optimal control of cavitation strengthening for the curved surface.

1. Introduction

Cavitation is a transient phase-change phenomenon that occurs in liquid medium. As cavitation bubbles collapse repeatedly near the solid surface, the solid surface might be strengthened and the fatigue life is improved thereby. Cavitation strengthening depends on multiple factors such as liquid medium properties, solid material properties and cavitation impact duration. Nevertheless, as cavitation impact is prolonged or the operation parameters improperly set, cavitation erosion might be induced [1]. In this case, the material surface is damaged and cavitation strengthening is meaningless. In practice, cavitation erosion in hydraulic machinery is typical. For some pumps used in marine engineering, cavitation constitutes a serious issue. Not just pump performance degrades as cavitation occurs, but also the noise emitted due to cavitation bubble collapse becomes traceable.

Cavitation can be produced in stationary or flowing liquid. Therefore, cavitation strengthening can be achieved under both the two conditions. In stationary liquid, vibratory or ultrasonic device can be used to induce cavitation. In flowing liquid, the situation is rather complex because cavitation is affected by flow parameter distributions and flow structures [2]. The development of cavitation producing techniques, as long as the variety of materials, has facilitated a deep understanding of cavitation strengthening, as is proved by the considerable amount of relevant literature published.

Regarding cavitation strengthening experiments, there is no standard for regulating the experimental rig or operation parameters. Until now, the international standard ASTM G134 turns out to be one of the few standards issued for instructing the experiments of cavitation erosion [3]. Such a standard proposes the optimum cavitation number for cavitation erosion. However, with respect to cavitation strengthening, the conclusions publicized hitherto are difficult to generalize.



Apart from experimental methods, numerical simulation plays an important role in the study of cavitation. The simulation related to cavitation usually covers fluid and solid aspects. For the former, computational fluid dynamics (CFD) technique has been used to solve equations governing the fluid flow [4]. Finite element method (FEM) enables the description of transient propagation of stress in the solid part. Until now, the validity of numerical simulation still suffers from debate. The most fundamental reason lies in the feasibility of the numerical model in terms of representing the physical essence of cavitation inception and cavitation evolution. In this context, diverse experimental results enhance instead of lowering the difficulty of unifying simulation codes. Furthermore, phenomena such as the crack initiation and erosion pits formation have not been accurately modelled numerically so far.

Two images showing the cavitation damage of hydraulic turbine blades are exhibited in Fig.1. It should be noted that the cavitation damage occurs under the influence of flow field characteristics. In Fig.1(a), the cracks located near the blade root are obvious. Serious consequence is appreciable as the cracks develop further. In Fig.1(b), an eroded zone involving many erosion pits is seen. The damage patterns shown in Fig.1 are complex due to their dependence on curved blades. In practice, effective measures should be taken in both optimal blade design and blade surface modification.

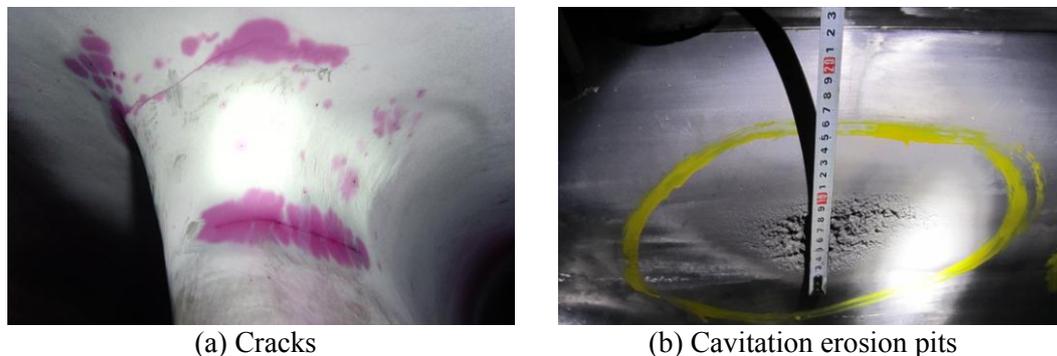


Figure 1. Damaged surface of hydraulic turbine blades.

The purpose of the present work is to explore the possibility of identifying cavitation effects in curved surface. Impeller blades used in marine engineering are employed as a representative. The chief factors influencing cavitation associated with these blades are analyzed. Based on experimental methods used for planar specimen surface, methods of inducing cavitation near curved blades and evaluating cavitation effects are proposed. The validity of these methods and characteristic results are illustrated. It is anticipated to offer some guidance for further work in laboratory level and to provide a reference for practical blade design as well.

2. Curved surface model and cavitation impact mechanism

A typical case of the curved surface is the impeller blade. In this context, an axial-flow impeller blade is shown in Fig.2. Axial-flow impeller pumps are widely used in marine engineering. The pump operation condition imposes cavitation on the pumps as a considerable threat.

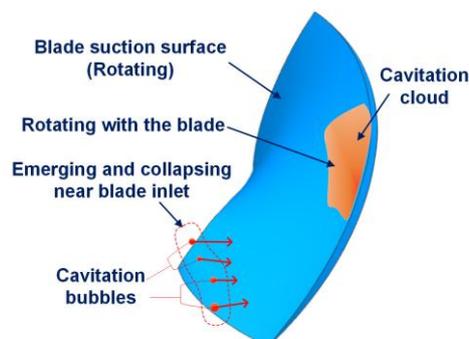


Figure 2. Schematic view of the effect of cavitation on curved surface.

Copper alloy and stainless steel are two commonly adopted materials for the pump blades used in marine engineering. Practical data only testify the cavitation erosion characteristics of pump impellers. It proves that the resistance of cavitation erosion of stainless steel is fairly higher. However, the anti-corrosion capability of the copper alloy is preferable. In Fig.3, the cumulative mass loss and cumulative mass loss rate of a stainless steel specimen under cavitation impact from a cavitating waterjet are plotted as the function of erosion time. The cumulative erosion rate is defined as the ratio of the cumulative mass loss to the erosion time. The entire cavitation impact process is divided into several stages. At initial stage, cavitation impact only leads to plastic deformation and mass loss is negligible. This stage is often named incubation stage as well. In the transitional stage, cracks initiate and some erosion pits that can be distinguished with naked eyes emerge, but the mass loss is still insignificant. In the mass loss stage, the mass loss increases sharply with the erosion time.

It should be noted that the entire cavitation impact process is dominated by cavitation bubble collapse near the specimen. Therefore, the cavitation strengthening should be implemented in the initial stage. Otherwise, the specimen will be damaged due to excessive cavitation impact. Furthermore, the operation parameters such as cavitation number must be properly set to avoid a sudden high-intensity cavitation impact, which also shifts the initial stage into transitional stage.

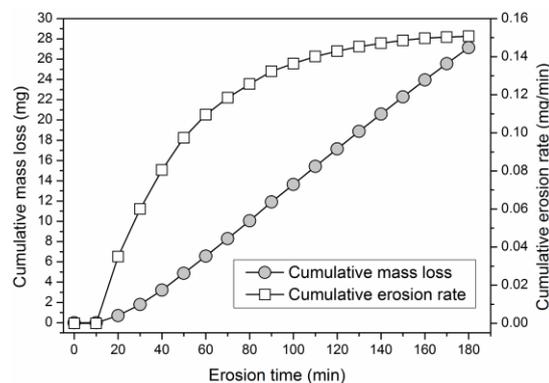


Figure 3. Mass loss of a stainless steel specimen due to cavitation impact.

Apart from the curved surface geometry that is difficult to depict, the complexity entailed with respect to impeller blades lies in that the eroded position is dependent of the liquid flow. As for the centrifugal pump impeller shown in Fig.4, the inlet part of the blade working surface is eroded, as differs from normal knowledge, which states that the eroded position appears in the blade back surface. This is related to the flow directions near the blade inlet. Meanwhile, cavitation strengthening of this part is expected to be attained with cavitating waterjet, as can impact the specified part as long as the jet can reach that part [5]. Of significance is the control of the strengthening time and jet stream angle because a full evaluation of the cavitation strengthening effect over the blade surface is hard to achieve.



Figure 4. Eroded working surface of a pump impeller.

3. Factors influencing cavitation erosion

An axial-flow impeller is exhibited in Fig.5. The highly curved blades are significantly different from the centrifugal blades shown in Fig.4. Furthermore, there is no front and back shrouds and the blades

are connected directly with the hub. The supporting manner will influence the hydraulic force and the crack initiation in the blade. During practical operation, it is impractical to disassemble the blades from the impeller to examine hardness or erosion pits. Therefore, in the laboratory level, model impellers, similar to the prototype in geometry, are usually employed for cavitation strengthening experiments.

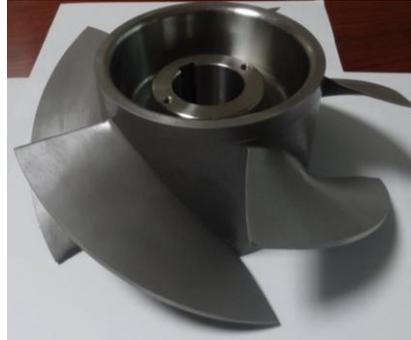


Figure 5. Axial-flow impeller.

4. Experimental methodology

A properly constructed experimental rig is the premise for obtaining physically meaningful results. The most distinct shortage in cavitation related experiments is that similarity laws cannot be used to transform the plastic deformation distribution or erosion pit size associated with the model to the prototype. Moreover, constructing an experimental rig requires a comprehensive consideration of all the primary operating factors. To detect and depict cavitation impact, the inspection techniques such as flow visualization and surface morphology observation should be considered during the design of the experimental rig [6]. In Fig.6, an experimental rig utilizing bubbles generated with submerged cavitating waterjet is schematically displayed. The side window of the test chamber is made transparent, so the light is allowed to penetrate into the liquid and then the light reflected can be received as well. The impeller can rotate with specified speed, and the jet stream angle can be adjusted. Therefore, the cavitating bubbles can arrive at any blade surface position.

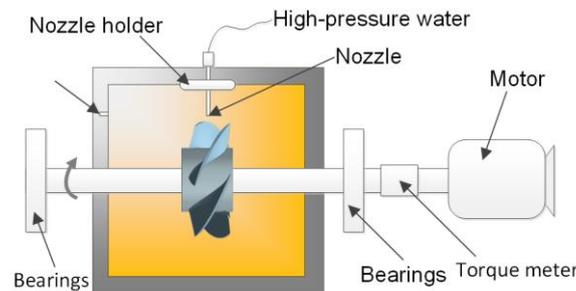


Figure 6. Cavitation experiment rig for impeller blades.

5. Evaluation of cavitation erosion

5.1. Hardness and residual stress

Hardness measurement is the most direct method of evaluating cavitation strengthening. As for flat specimen, Vickers microhardness can be measured with general microhardness tester. For curved blade surface, only part of the entire blade surface can be detected with the commonly used microhardness tester. The coverage is also determined by blade geometry. Furthermore, the obtained microhardness values from the curved blade must be calibrated.

As shown in Fig.7, the residual stress in a stainless steel specimen, which is subjected to the cavitating jet impact, is plotted as the function of cavitation impact time. Additionally, the distribution of microhardness in the direction vertical to the impacted surface can also be utilized to illustrate the cavitation impact intensity.

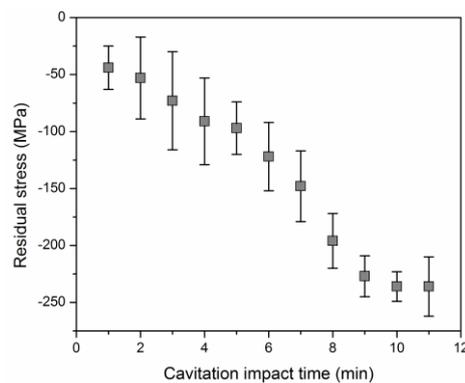


Figure 7. Variation of residual stress in the specimen with cavitation impact time.

5.2. Surface morphology observation

Conventional scanning electron microscope can be used to observe the surface impacted by cavitation bubble collapse. But this method cannot offer a three-dimensional description of the impacted surface. Surface morphology characteristics reflect the influence of cavitation bubble collapse on specimen surface [7]. Modern three-dimensional optical profiling system allows the acquisition of the local heights in the eroded surface. Moreover, the resolution can reach the micron level.

Two images constructed based upon the data captured with an Axio CSM 700 confocal light microscope are shown in Fig.8. The two sampled surfaces were impacted at different durations of cavitating waterjet. In Fig.8(a), it is seen that plastic deformation is predominant and no erosion pits are seen. In this stage, cavitation strengthening is attained. With the elongation of the cavitation impact, erosion pits emerge, as can be identified in Fig.8(b). In this context, the surface is damaged. Therefore, the most influential operation parameters should be specified.

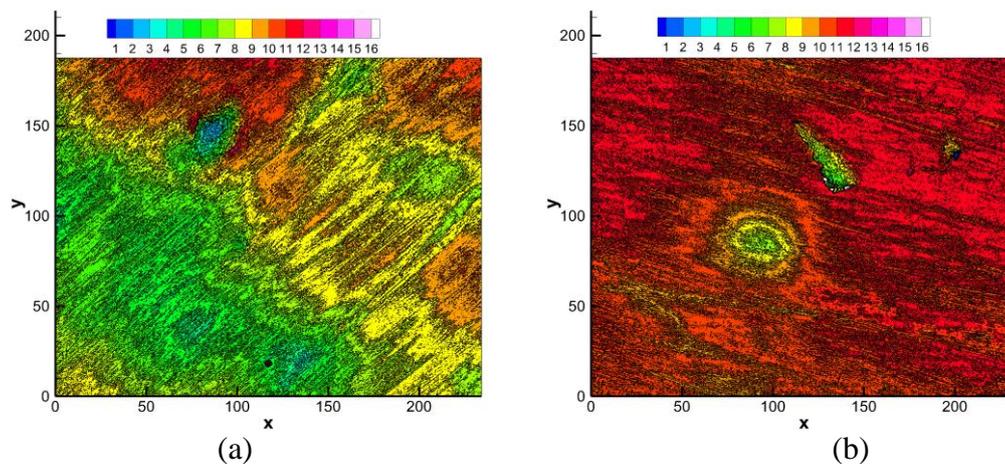


Figure 8. Surface morphology of cavitation impacted surface. The two images were obtained at different cavitation impact moments, and the unit in the images is μm .

5.3. Impact force measurement methods

Cavitation effect behaves as the impact force over the impacted specimen surface. The impact force magnitude and loading frequency can be used to describe the cavitation effect. The polyvinylidene fluoride (PVDF) sensor attached to the back of the specimen was attempted to measure the impact force exerted on the specimen surface [8]. Moreover, the response of the PVDF sensor is adequately fast, the data acquired with such a sensor can be used to investigate transient evolution of cavitation bubbles. For curved blades, there are two aspects that deserve further consideration. One is the PVDF film should be sealed properly to avoid the damage to the film by cavitation bubble collapse; the other aspect lies in the blade thickness, which will influence cavitation impact signal transfer as the PVDF

sensor is mounted in the other side of the impacted surface. In recent years, acoustic methods have been attempted in the study of cavitation. With the hydrophone or acoustic energy sensor, acoustic signals emitted with the collapse of cavitation bubbles are recorded. Then signal processing techniques are employed to extract signals associated with cavitation.

With the above-mentioned methods, the cavitation strengthening effect in the blade surface is expected to be assessed. In many occasions, there is no unified principle for the application of these methods, and the benchmark experimental data are absent. Therefore, it is preferable to use two or three methods jointly to eliminate non-physical data due to improper calibration of a single instrument.

6. Conclusions

Cavitation is a complex phenomenon that calls for generalizable conclusions. How to utilize cavitation effect remains a subject of active research. In the present work, the cavitation strengthening of curved surface is proposed, and the impeller blades used in marine engineering are taken as a representative. The cavitating waterjet is used to induce cavitation and then to offer a sound measure for strengthening impeller blades with consistent cavitation bubble collapse.

Based upon the general knowledge of cavitation inception and cavitation strengthening, primary factors that influence the experiment of cavitation impact of the impeller blade are explained comprehensively. Practical cases of cavitation effect associated with impeller blades are explained to establish the correlation of laboratory research and industrial practice.

The methods for evaluating cavitation strengthening effect are critical for obtaining both qualitative and quantitative conclusions. Here, several methods that can be used to study cavitation effect in the curved surface are presented and discussed. In consideration of the impeller structure and the curved blade, two or three methods are anticipated to be used in combination. The suitability of these methods deserves further investigation and validation.

Acknowledgments

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References

- [1] B.K.Sreedhar, S.K.Albert, A.B. Pandit, Cavitation damage: Theory and measurements- A review, *Wear* 372-373 (2017) 177-196.
- [2] Ezddin Hutli, Milos S. Nedeljkovic, Nenad A. Radovic, Attila Bonyár, The relation between the high speed submerged cavitating jet behaviour and the cavitation erosion process, *Int. J. Multiph. Flow* 83 (2016) 27–38.
- [3] ASTM Standard, G134-95, Standard test method for erosion of solid materials by a cavitating liquid jet, *Annual Book of ASTM Standards*, 03.02, 2010, 558-571.
- [4] Hai-xia Liu, Qi-ming Shao, Can Kang, Chen Gong, Impingement capability of high-pressure submerged water jet: Numerical prediction and experimental verification, *J. Cent. South. Univ.* 22(2015)3712-3721.
- [5] H. Soyama, Y. Sekine, Sustainable surface modification using cavitation impact for enhancing fatigue strength demonstrated by a power circulating-type gear tester, *Int. J. Sust. Eng.* 3(2010) 25–32.
- [6] Haixia Liu, Can Kang, Wei Zhang, Tao Zhang, Flow structures and cavitation in submerged waterjet at high jet pressure, *Exp. Therm. Fluid Sci.* 88(2017)504-512.
- [7] Can Kang, Haixia Liu, Tao Zhang, Qing Li, Investigation of submerged waterjet cavitation through surface property and flow information in ambient water, *Appl. Surf. Sci.* 425(2017)915-922.
- [8] A. Sahaya Grinspan, R. Gnanamoorthy, Impact force of low velocity liquid droplets measured using piezoelectric PVDF film, *Colloids Surf., A* 356 (2010) 162-168.