EXPERIMENTAL INVESTIGATION OF ULTRASONIC CAVITATION EROSION: IMPLICATIONS FOR WATER TURBINES AND HYDRAULIC MACHINERY

LUKA KEVORKIJAN, TILEN JERNEJC, LUKA LEŠNIK, IGNACIJO BILUŠ

University of Maribor, Faculty of Mechanical Engineering, Maribor, Slovenia
luka.kevorkijan@um.si, tilen.jernejc@um.si, luka.lesnik@um.si, ignacijo.bilus@um.si

Cavitation erosion is a major concern in water turbines and hydraulic machinery, where bubble collapse near solid surfaces leads to material degradation and reduced efficiency. In this study, ultrasonic cavitation tests were conducted using a Sonics VCX-750 ultrasonic vibratory apparatus operating at 20 kHz to investigate erosion behaviour of aluminium and steel specimens under identical conditions. The sonotrode tip was submerged 30 mm below the water surface, with amplitude of 30 μm and fluid temperature maintained at 17 °C. High-speed imaging at 100,000 frames per second captured bubble dynamics. After 3 hours of exposure, surface photographs revealed significantly more extensive erosion on aluminium compared to steel, demonstrating higher resistance of the latter to cavitation. The results highlight the importance of material selection in hydraulic applications and provide insights into cavitation mechanisms relevant to the durability and performance of water turbines.

DOI
https://doi.org/10.18690/um.fs.7.2025.23

ISBN
978-961-299-049-7

Keywords:
cavitation erosion,
hydraulic machinery,
ultrasonic cavitation,
water turbines,
material selection

University of Maribor Press

1 Introduction

Cavitation is a critical phenomenon in hydraulic machinery such as water turbines, pumps, valves and marine propellers, where rapid pressure fluctuations cause the formation and violent collapse of vapor bubbles. The implosion of these bubbles near solid surfaces generates intense micro-jets and shock waves, leading to material damage known as cavitation erosion. This degradation not only shortens the service life of components but also reduces efficiency and reliability, resulting in significant operational and maintenance costs. Understanding cavitation erosion mechanisms is therefore essential for improving the durability and performance of hydraulic systems.

Experimental studies of cavitation in full-scale water turbines are challenging due to the complexity of flow conditions, high costs, and limited accessibility for in-situ observations. Consequently, laboratory-scale methods are widely employed to simulate cavitation and to evaluate material resistance under controlled conditions. Among these, ultrasonic vibratory cavitation testing using a sonotrode has become a standardized and effective approach for accelerated erosion assessment. The ultrasonic method creates highly localized cavitation zones, enabling systematic analysis of bubble dynamics, erosion mechanisms, and comparative material performance. In addition to erosion quantification, the visualization of cavitation plays an important role in linking laboratory experiments to real hydraulic applications. High-speed imaging provides insight into the formation, collapse, and spatial distribution of cavitation bubbles, which closely resemble the microscale processes occurring inside hydraulic machinery, for example turbine blades or valve gates under cavitating flow.

Numerous studies have sought to understand cavitation erosion in hydraulic machinery through both field observations and laboratory investigations. Field measurements on turbines and pumps have provided valuable evidence of erosion patterns, typically concentrated near runner blades, guide vanes, and draft tubes where pressure fluctuations and vortex structures are most intense [1], [2], and [3]. However, the complexity of large-scale flows has limited the ability to directly correlate bubble dynamics with erosion mechanisms. To overcome these challenges, researchers have turned to model testing and accelerated laboratory techniques.

Recently computational approaches to predict erosion from CFD simulations have emerged as complementary approach to experimental approaches.

Ultrasonic vibratory cavitation testing has been widely adopted as a standardized method (ASTM G32) for laboratory scale material erosion assessment [4]. This technique enables the generation of stable cavitation zones, allowing systematic evaluation of erosion rates and material degradation. Previous works have focused on identifying material parameters which influence material response to cavitation – cavitation erosion. Franc [5] proposed a model which describes cavitation erosion of work-hardening materials. Cavitation aggressiveness in ultrasonic cavitation was studied by Du and Chen [6] by combining experimental approaches with CFD simulations, showing that microstructural features such as hardness, grain size, and phase distribution strongly influence erosion. In a more material focused experimental study, Ye et al. [7], observed the material response, particularly change in Vickers hardness. High-speed visualization studies have further revealed the role of transient bubble collapses and micro-jets in initiating and propagating surface damage [8]. Despite these advances, most studies focus on quantitative erosion rates, with fewer works linking observed bubble dynamics to material-specific erosion mechanisms in a way that directly connects laboratory testing to hydraulic machinery.

The present study investigates cavitation erosion using an ultrasonic sonotrode under controlled laboratory conditions. High-speed imaging was employed to capture cavitation dynamics. Erosion was observed on aluminium and steel samples to examine and differentiate material-specific erosion patterns. The experimental findings are discussed in the context of hydraulic machinery.

2 Methods

Cavitation erosion experiments were conducted using an ultrasonic vibratory apparatus (Sonics VCX-750) operating at the standard frequency of 20 kHz. The sonotrode tip was positioned 30 mm below the free surface of tap water in a transparent test tank. The vibration amplitude was set to 25 % of the maximum rated amplitude of the device, which resulted in approximate amplitude of 30 μm. The water temperature was maintained at 17 °C using an additional closed-loop cooling system to ensure consistent operating conditions throughout the test.

Experimental setup for investigation of ultrasonic cavitation erosion at the Turbomachinery Laboratory of the Faculty of Mechanical Engineering, University of Maribor is shown in Figure 1.

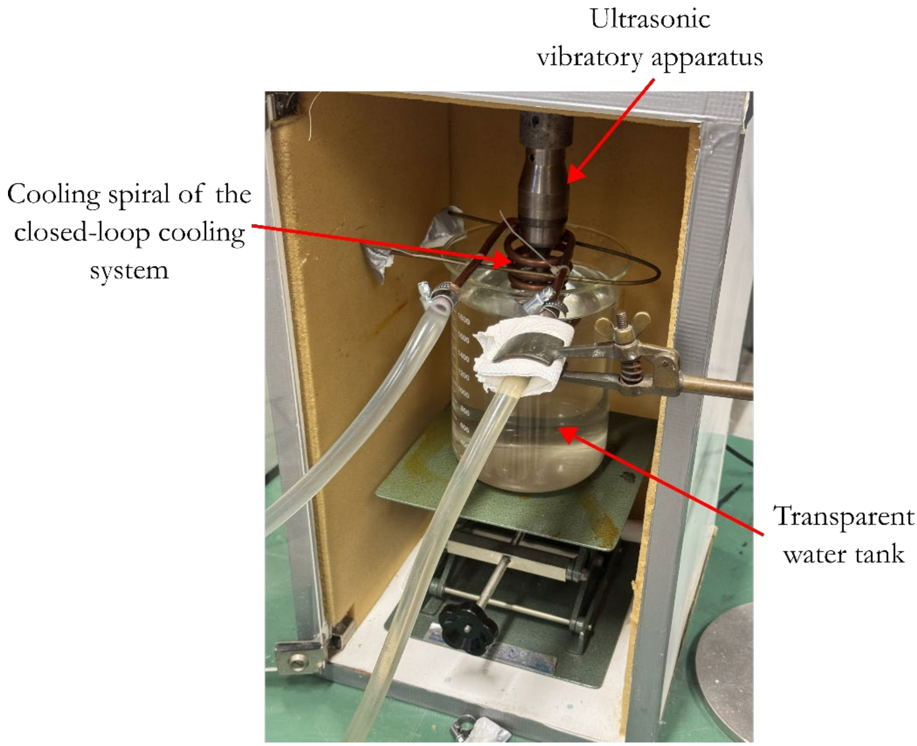

Figure 1: Experimental setup for investigation of ultrasonic cavitation erosion.

Two metallic materials, aluminium and steel, were selected as test specimens. Test specimens were produced as replicable threaded tips for the sonotrode with 13 mm in diameter, shown in Figure 2. Both materials were subjected to identical cavitation conditions. Each test was run for a total duration of 3 hours, after which the specimens were removed for surface examination. The identical test conditions allowed a direct comparison of erosion behaviour between the two materials.

High-speed imaging was employed to observe cavitation activity in the vicinity of the sonotrode with the setup shown in Figure 3.

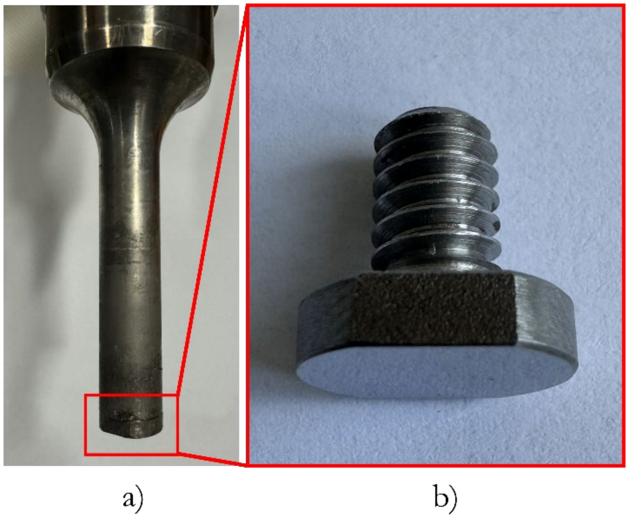

Figure 2: Ultrasonic vibratory apparatus tip: a) view of the full vibrating apparatus with replaceable tip, b) replaceable threaded tip used as sample to study cavitation erosion, displayed is steel tip.

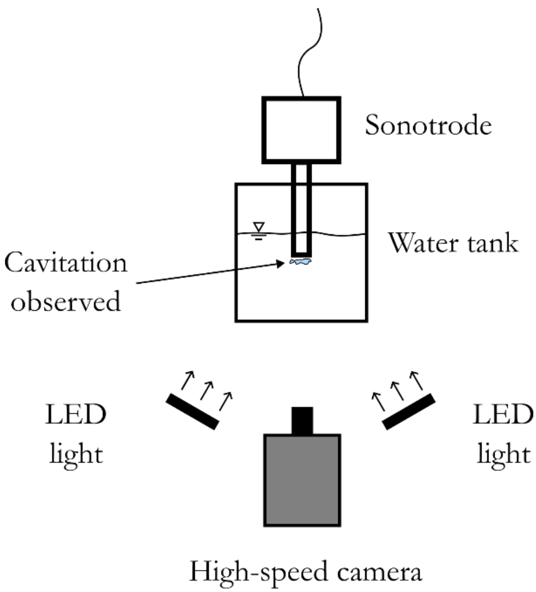

Figure 3: Schematic view of experimental setup for high-speed filming.

A Photron Fastcam SA-Z high-speed camera was used, recording at 100,000 frames per second. Illumination was provided by GSVITEC Multiled LED lights (GSV_G8_KIT) with a correlated color temperature of 6500 K and a luminous flux of 12,000 lumens, ensuring sufficient lighting.

After testing, the eroded surfaces of the aluminum and steel specimens were documented by photography. These images provide a qualitative assessment of erosion patterns and damage characteristics, which are then related to the cavitation dynamics observed in the high-speed recordings.

The chosen materials are directly relevant to hydraulic machinery: steel is traditionally used for turbine runners and hydraulic components due to its strength and durability, while aluminium alloys are increasingly considered as alternatives in certain applications because of their low weight and manufacturability. Comparing their cavitation erosion response under identical laboratory conditions therefore offers insights into material selection and long-term performance in water turbines and other hydraulic systems.

3 Results

First, we present the results of high-speed filming of acoustic cavitation phenomenon in Figure 4 where pictures covering one full cycle are shown (peak-to-peak movement of the sonotrode tip). High-speed recordings revealed the formation of dense cavitation clouds at the sonotrode tip. The bubble dynamics were characterized by rapid growth and collapse cycles, consistent with the periodic pressure oscillations at 20 kHz. Bubble collapses were frequently observed close to the specimen surfaces (see Figure 4 e and f for example), producing localized high-intensity events. We can see two distinct cavitation zones. The first zone features larger cavitation structures (macroscopic bubbles) attached to the sample surface in a band near the circular edge of the sample (pointed out on Figure 4 a) outline drawn with red dotted line). The second zone features a narrow column of microscopic bubbles extending radially from the axis of tip movement and bellow the tip towards the bulk liquid (pointed out in Figure 4 b).

The zone of attached larger cavitation structures corresponds well to the area of maximum erosion observed on the samples as shown in Figure 5. These observations are consistent with previously reported mechanisms of micro-jet and shock wave formation during bubble implosion which are most erosive when cavitation is in proximity with the solid surface and recognized as primary causes of cavitation erosion in hydraulic machinery.

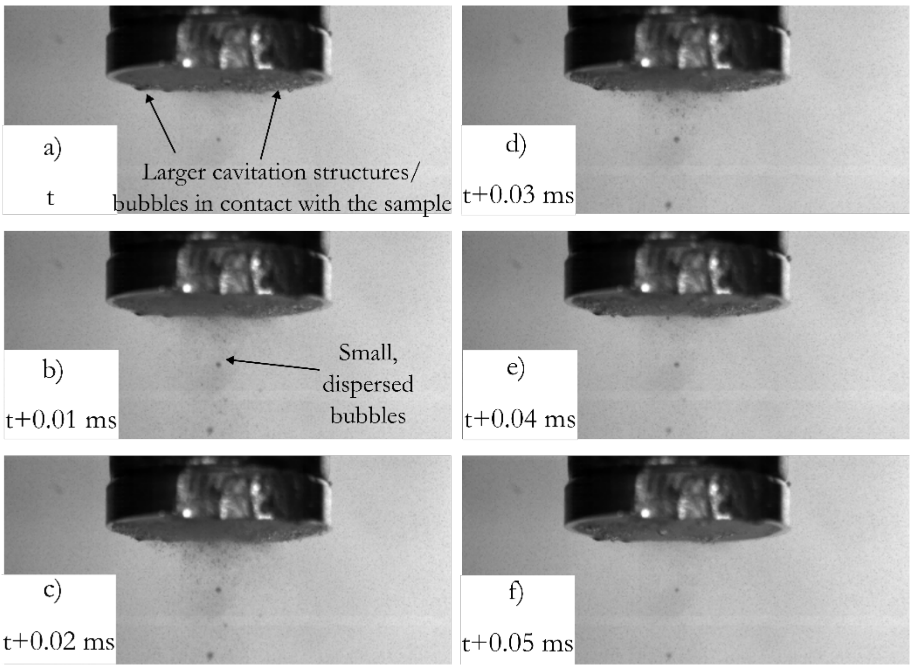

Figure 4: Results of filming with high-speed camera. From a) through f) a full cycle (peak-to-peak amplitude) of sonotrode tip movement is shown with cavitation structures pointed out.

However, some differences can be observed between aluminium and steel samples, particularly when looking at the state of the surface at intermediate time (60 minutes of exposure). In the case of aluminium, pronounced surface damage was visible already after 60 minutes, characterized by extensive pitting and roughening of the surface, particularly larger pits can be seen in Figure 5 c). Then at final time of 180 minutes, the material exhibited a relatively large eroded area, suggesting lower resistance to cavitation.

In contrast, the steel specimen showed only small pits after 60 minutes of exposure. After 180 minutes more localized damage, with distinct larger pits can be seen. In comparison to aluminium sample after same duration of exposure, less overall surface degradation is visible. These differences indicate that steel exhibits a higher intrinsic resistance to cavitation erosion under the tested conditions.

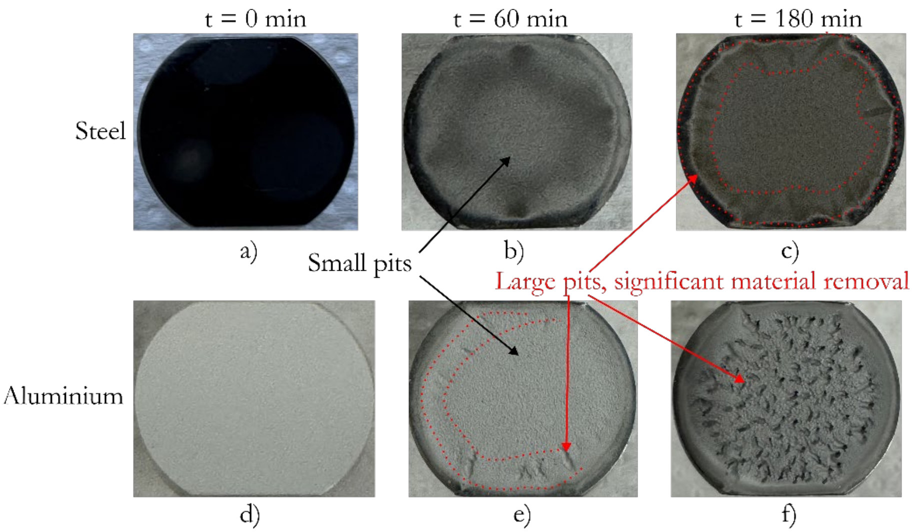

Figure 5: Steel and aluminium samples shown at various times: a) and d) before exposure to cavitation, b) and e) after 60 minutes exposure to cavitation and c) and f) after 180 minutes exposure to cavitation.

The results highlight the critical role of material selection in mitigating cavitation erosion in water turbines and other hydraulic components. While steel remains the conventional choice for turbine runners and guide vanes due to its durability, aluminium alloys are being considered for certain applications where reduced weight and ease of manufacturing offer advantages. However, the present findings indicate that aluminium is significantly more susceptible to cavitation damage under identical operating conditions, which may limit its applicability in erosion-prone regions of hydraulic machinery. High-speed visualization provided further insight by linking the bubble collapse dynamics to observed surface damage, thus bridging laboratory-scale testing with real cavitation erosion mechanisms in turbines.

4 Conclusion

Overall, the combined use of ultrasonic cavitation testing, high-speed imaging, and post-test surface inspection provided a comprehensive picture of cavitation erosion processes. The study reinforces the importance of material resistance in prolonging the service life of hydraulic machinery and underscores the value of laboratory testing for predicting field performance.

Acknowledgments

The authors acknowledge the financial support from the Slovenian Research Agency (research core funding No. P2-0196).

References

[1] Brennen, C. E. (1995). *Cavitation and Bubble Dynamics*. Oxford University Press.
[2] Franc, J. P., and Michel, J. M. (2004). *Fundamentals of Cavitation*. Kluwer Academic Publishers, Dordrecht.
[3] Avellan, F. (2004). Introduction to Cavitation in Hydraulic Machinery. Presented at the 6th International Conference on Hydraulic Machinery and Hydrodynamics, Timisoara, Romania, October 21-22, 2004.
[4] ASTM G32-16. "Standard Test Method for Cavitation Erosion Using Vibratory Apparatus." ASTM International, West Conshohocken, PA, 2016.
[5] Franc, J. P. (2009). Incubation Time and Cavitation Erosion Rate of Work-Hardening Materials. *Journal of Fluids Engineering*, 131, 021303. doi: 10.1115/1.3063646
[6] Du, J., and Chen, F. (2021). Cavitation dynamics and flow aggressiveness in ultrasonic cavitation erosion. *International Journal of Mechanical Sciences*, 204, 106545. doi: 10.1016/j.ijmecsci.2021.106545
[7] Ye, L., Zhu, X., Wei, X., and Wu, S. (2020). Damage characteristics and surface description of near-wall materials subjected to ultrasonic cavitation. *Ultrasonics – Sonochemistry*, 67, 105175. doi: 10.1016/j.ultsonch.2020.105175
[8] Reuter, F., Deiter, C., and Ohl, C.-D. (2022). Cavitation erosion by shockwave self-focusing of a single bubble. *Ultrasonics Sonochemistry*, 90, 106131, doi: 10.1016/j.ultsonch.2022.106131