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Experimental Investigation of Inception Cavitation Phenomena Effect in Centrifugal Pumps Using Hydrophone Sensor

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Abstract

The objective of this work is to develop methodology for identifying and detecting cavitation in centrifugal pumps, with a specific focus on the Lowara CEA 210/2 pump. This pump is widely used across various sectors, including agriculture, industry, and residential settings. Cavitation is a phenomenon where vapor bubbles form in a liquid due to pressure drops and then collapse, causing shockwaves that can damage the pump components and degrade its performance. This often occurs under turbulent flow conditions and can severely affect the efficiency and longevity of the pump. Accurate detection and assessment of cavitation are essential for maintaining pump reliability, minimizing maintenance costs, and prolonging its operational lifespan. In this study, four distinct levels of cavitation were identified, each associated with different flow rates. These levels impact efficiency of pump and overall performance, highlighting the need for precise monitoring to prevent significant operational issues. To monitor and analyze cavitation, the study employed a hydrophone for capturing acoustic signals and utilized time-domain analysis techniques. The Cavitation Detection Index (CDI) was found to be an effective tool for detecting and estimating cavitation, especially at its early stages. The CDI measures acoustic signals to provide insights into cavitation severity, enabling early intervention. Experimental results indicated that the low frequency range of acoustic signals is particularly effective for early cavitation detection. By focusing on these low-frequency components, the CDI allows for timely identification of cavitation, which can significantly enhance the pump's longevity and operational efficiency. This proactive approach not only helps in extending the pump's service life but also optimizes its performance by addressing cavitation issues before they lead to more severe damage.

Keywords: centrifugal pump, flow rate, rotational speed, acoustic signal, cavitation, hydrophone.

1. Introduction

The centrifugal pump is a mechanical device used to raise liquids from one level to another using low pressure at the pump's inlet and high pressure at its exit[1], [2]. It has various applications in industries such as infrastructure, agriculture, civil engineering, and water and sewage transmission networks[3], [4]. Pumps have a wide range of uses in the industry, including infrastructure, agriculture, civil engineering, and water and sewage transmission networks. For example, in a petrochemical unit, centrifugal pumps make up about 80% to 90% of all the pumps[4], [5]. In a petrochemical unit, centrifugal pumps are predominantly utilized for fluid transfer, supplying feedstock to processes, circulating cooling fluids, managing wastewater, and loading finished products. These applications are essential for ensuring the efficiency and continuity of operations within the facility.[6] However, two significant issues persist: flow instability caused by pressure pulsations and cavitation erosion[7], [8]. Cavitation occurs when the internal absolute static pressure drops below the water's saturation vapor pressure at the designated temperature[9], [10]. Shock waves are responsible for cavitation erosion, which can seriously erode the surface[11] Solving these problems has become more important as centrifugal pump design has grown[12], [13]. The most significant problem is cavitation, when the pressure drops, vapor bubbles form within the liquid. As these bubbles travel through the pump and enter regions of higher pressure, [14]they collapse violently, generating shock waves. This phenomenon can lead to significant damage, including pitting and erosion of the pump components, particularly the impeller and casing. Valve cavities typically appear at the leading edge of the blades[15], near the suction of the impeller. Cavitation is a detrimental phenomenon that negatively impacts the performance of centrifugal pumps, leading to accelerated wear of internal components, increased noise levels, and a reduction in hydraulic efficiency[16]. The hydrophone has emerged as an effective tool for early cavitation detection due to its

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ability to capture the distinctive acoustic signals generated by the collapse of vapor bubbles within the fluid. This approach offers the dual advantage of mitigating cavitation-related damage and preserving operational efficiency. By detecting cavitation in its initial stages, corrective actions can be implemented to minimize potential damage and reduce maintenance costs[17], [18].**Jiaxing Lu et al. (2021)**[19]the study combines numerical and experimental methods to detect the inner flow state of a centrifugal pump. It found that blade inlet attack angles significantly influence flow instabilities. The mechanism of rotating stalls in the impeller channel was explained. Flow state identification with vibration (FSIV) was proposed to identify flow instabilities, ensuring safe and steady system conditions.**Xiaohui Liu et al. (2023)** [20]: This study investigates the use of pressure pulsation, vibration, noise, and acoustic emission signals as cavitation defect detection techniques. It is discovered that cavitation is more sensitive to low frequencies, and the most precise method is time-frequency analysis. Although the acoustic emission approach has shortcomings, it is not as commonly employed as other methods to identify cavitation beginning. For a quick and simple way to show cavitation data, the study recommends characterizing cavitation intensity using the acoustic approach.**Wentao Su et al. (2023)** [21]:The energy distribution of initial cavitation noise and its fluctuation with the cavitation coefficient are investigated in this work. It offers a method based on sound energy and bubbles produced by cavitation for determining the early stages of cavitation in the runner blades of hydraulic gear. The cavitation noise qualities are analyzed using the energy distribution analysis approach, which also suggests a mathematical model for the time-frequency features. The study discovers that when the cavitation coefficient rises, the high- and low-frequency energy distributions change significantly close to cavitation, with decreasing slopes and ratios.**Mina L. Kerellouset al. (2024)** [22]**:**The study investigated cavitation in a centrifugal pump with a semi-open impeller under different operating conditions. It found a direct correlation between cavitation levels, rotating speed, and pump flow rate. Vapor bubbles formed along the impeller blades and near the impeller's eye. Suction pressure increased with speed reduction, with 8% and 21% increase for 6% and 12% speed reductions, respectively. **José Fernandeset al. (2024)**[23]**:** The study explores the impact of ultrasonic waves at 20 kHz on acoustic cavitation in a water-filled chamber. It examines the influence of different radiator geometries on cavitation production at different electrical energy levels. The study uses a piezoelectric sensor to measure cavitation at different power settings. Results show that solid geometric shapes primarily affect the cavity axially, while perforated shapes increase cavity density at low energy levels. The piezoelectric sensor's efficiency in sensing sonic cavitation is demonstrated. **Calvin Stephenet al. (2024)**[24]: In micro-hydropower applications, a study has created a new technique for detecting cavitation in Pumps-as-Turbines (PATs). Researchers employed probability density functions to calculate the Deviation from Normal Distribution (DND) from vibration signals that they had captured. The procedure enhanced the ability to detect cavitation and gave PAT condition monitoring users unambiguous alarm limits. The technique proved to be responsive, reliable, and independent of operating speed at different cavitation levels and operating speeds. Reliable micro-hydropower system operation and maintenance depend on this improved DND-based technique. The aim of this study is to provide a practical and straightforward solution with significant benefits for industrial applications by investigating the behavior and distribution of bubbles at the impeller inlet of a centrifugal pump, identifying the onset of cavitation, and evaluating the pump's cavitation performance. The study focuses on a methodology that utilizes a single hydrophone for effective cavitation detection and prevention. By analyzing how cavitation interacts with various operational parameters, such as pressure, impeller speed, and flow rate, this study seeks to enhance understanding of cavitation dynamics, ultimately contributing to improved pump performance and longevity. This approach offers a clear and professional summary of the study's objectives and scope, emphasizing its industrial relevance and application potential.

2. Experimental Test rig

The experimental test rig, depicted in Figure (1),the experimental setup components are displayed in Table (1) is designed to assess cavitation in centrifugal pumps and is composed of several key components:

1. **Variable-Frequency Drive Motor**: This motor controls the rotational speed of the pump by adjusting the frequency of the electrical supply. It allows for precise control of pump speed and flow conditions, essential for simulating various operational scenarios.
2. **Centrifugal pump type(CEA 210/2):** The centrifugal pump used in this experimental study is shown in Figure (1). This kind of pump has a closed-type, single-stage impeller. It is driven by a 3.phase, 0.75 kW, 1.1 HP motor. 2.17A is the current. This pump has eight impeller blades, a design rotational speed of 2850 rpm, a head of approximately 17.5 m at the intended flow rate, and a maximum flow rate of 300 (L/min) [25].

Figure 1. Centrifugal pump type CEA 210/2.

3. **Inlet and Outlet Pipes**: These pipes facilitate the flow of water into and out of the **pump**, ensuring that the system can be tested under different flow rates and conditions.
4. **Inlet and Outlet Valves**: These valves regulate the flow of water into and out of the pump, enabling the adjustment of flow rates and pressure conditions during testing.

5. **Water Tank**: The tank provides a clear view of the water level and flow, **allowing** for visual inspection and monitoring of the pump’s performance and cavitation effects.
6. **Air Vent Valve**: This valve is used to release trapped air from the system, which **helps** in maintaining proper pump operation and preventing airlocks.
7. **Mechanical Valve for Water Entry**: This valve controls the entry of water into the system, ensuring accurate flow **measurement** and system operation.
8. **Cavitation Tank**: A dedicated tank designed to simulate and monitor cavitation phenomena within the pump, crucial for assessing the impact of cavitation on pump performance.
9. **Safety Valve**: This valve ensures the system operates within safe pressure limits, preventing over-pressurization and potential damage to the equipment.
10. **Hydrophone (Model ASF-1MKII)**: cavitation in pumps causes noise levels to rise. As a result, a hydrophone was employed in this investigation to track and gather additional data on the cavitation. An accurate free-field hydrophone model ASF-1 MKII frequency response [26] (7Hz–90 kHz) as shown in Figure (2).The hydrophone is used to detect and measure acoustic signals associated with cavitation. It provides real-time data on cavitation intensity and helps in evaluating the effectiveness of cavitation detection methods.
11. **Pressure Sensor:** These sensors monitor the pressure within the system, specifically near the pump’s inlet and outlet. By measuring the pressure at these critical points, the sensors help ensure safe operating conditions and provide valuable data to prevent cavitation by detecting any significant pressure drops that could lead to bubble formation.
12. **Temperature Sensor:** This sensor measures the temperature of the fluid within the system. Temperature data is essential for maintaining operational efficiency and avoiding overheating, which could affect flow dynamics and increase cavitation risk.
13. **Motorized Electrical Ball Valve:** This electrically controlled valve adjusts the flow of fluid in the system based on electronic signals, allowing automated flow control to achieve the desired flow rates or shut down the flow if needed for safety.
14. **Water Flow Meter Sensor:** This sensor measures the rate of water flow through the system. It provides crucial data to ensure that the flow rate meets the system’s requirements, which is important for both efficiency and cavitation prevention.
15. **Foundation**: A substantial foundation supports the test rig and minimizes interference from system vibrations, ensuring accurate and reliable measurements.

By varying the settings of the variable-frequency drive motor and adjusting the degree of valve openings, the test rig can simulate various pump speeds and flow conditions. This setup allows for comprehensive testing and analysis of cavitation effects on the pump’s performance.

Figure 2. hydrophone model of ASF-1 MKII

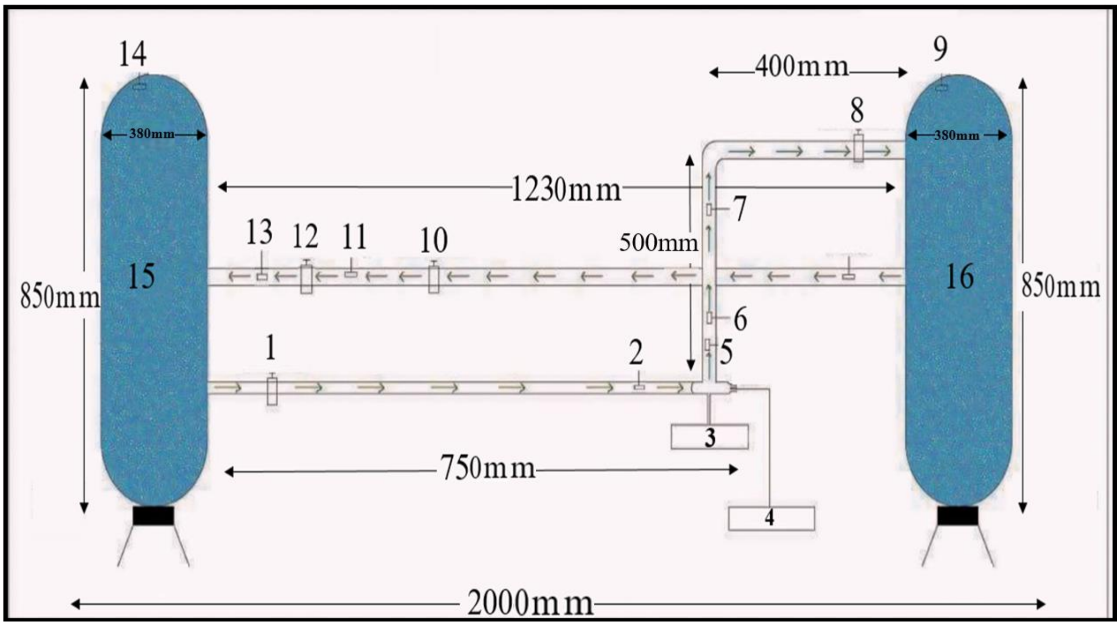


Figure 3. schematic Test rig

Table 1. the experimental setup components

N0.	The parts
1	Mechanical valve
2	Pressure sensor
3	Centrifugal pump CEA 210/2
4	AC drive
5	Temperature sensor
6	Hydrophone
7	Pressure sensor
8	Mechanical valve
9	Safety valve
10	Motorized Valve Electrical Ball Valve
11	Water flow meter sensor
12	Mechanical valve
13	Pressure sensor
14	Safety valve, Mechanical valve for water entry
15	water Tank
16	Water Tank

3. Equations for Determining Pump Efficiency, Total Head, and Cavitation Analysis Parameters

The following equations (1),(2) are utilized to determine the pump's efficiency, η, and total head, H_{tot}, respectively[27], [28].

$$H_{\text{tot}} = H_{\text{tot\_Dis}} - H_{\text{tot\_Suc}}$$
$$= \left(\frac{p_{\text{Dis}} - p_{\text{Suc}}}{\rho g}\right) + \left(\frac{v_{\text{Dis}}^2 - v_{\text{Suc}}^2}{2g}\right) + Z \quad (1)$$

$$\eta = \frac{\rho g H_{\text{tot}} Q}{P_{\text{mech}}} = \frac{\rho g H_{\text{tot}} Q}{P_{el}\eta_{\text{mot}}} \quad (2)$$

Where the mean pipe velocity and static pressure during discharge and suction are denoted, respectively, by $v_{\text{Dis},}^2$ v_{Suc}^2, p_{Dis}, and p_{Suc}. Z represents the vertical separation between the suction and discharge measurement locationsρ: is the density of the fluid g: is the gravitational acceleration: is the total head achieved by the pump, Q denotes the flow rate, P_{mech} stands for mechanical power, and P_{el}stands for electric power Extracted from the motor and ηmot the efficiency of the motor. The dimensionless Thomas's cavitation number, σ, for the analysis of the two-phase flow inside the pump is used to calculate the Net Positive Suction Head (NPSH), which is the difference between the vapor pressure, H_V, and the total pressure in the suction side, $H_{\text{tot\_Suc}}$, both stated in head units. Lastly, equations (3), (4), (5), (6). Present the dimensionless parameters of the pump for the flow rate, Φ, head, Ψ, and power, N[28], [29].

$$\sigma = \frac{NPSH}{H_{\text{tot}}} = \frac{H_{\text{tot\_Suc}} - H_V}{H_{\text{tot}}} \quad (3)$$

$$\Phi = \frac{c_{2n}}{u_2} \quad (4)$$

$$\Psi = \frac{2gH_{tot}}{u_2^2} \quad (5)$$

$$N = \frac{P_{\text{mech}}}{\rho\Omega^3 D^5} \quad (6)$$

Where D is the impeller diameter, u2 is the impeller's circumferential velocity, and c2n is the radial component of the absolute flow velocity at the impeller outlet.

4. Conventional statistical analysis in the time domain

Analysis of peak values: the peak signal calculation is an important statistical metric.

RMS value : The RMS value is defined by the following equation (7) [30], [31]:

$$\text{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2}, \quad (7)$$

Where N and $x_i$stand for the total number of elements and the element signal, respectively.

Peak-to-peak value: This is the third statistical measure applied in this study.

Value of variance Equation (8) can be used to compute the variance value[32], [33]:

$$\text{Variance} = \frac{\sum (x_i - \bar{x})^2}{N-1} \quad (8)$$

Where N,x_i and the sum of the elements are the elements' mean values, the set of elements, and the total number of elements, respectively.

Respectively: Analysis of mean value the following equation is used to compute the mean value[34], [35]:

$$\mu = \frac{1}{N}\sum_{i=0}^{N-1} x_i. \quad (9)$$

5. Result and discussion

The condition monitoring method finds significant patterns in auditory signals using statistical analysis. In order to predict and identify pump cavitation, this section of the study examines time-domain acoustic data. The study's main objective is to identify cavitation in centrifugal pumps by using acoustic analytic techniques. The results demonstrate that when the pump runs, internal recirculation at the discharge and suction zones generates extra hydraulic noise. When the pump operates at a flow rate higher than designed, flow turbulence, excess hydraulic noise, and cavitation all contribute to an increase in overall noise. If the flow rate is less than 240 (L/min), there is no discernible change in the peak and RMS features. However, when the flow rate is higher than 240(L/min), the amplitude of the acoustic waves rapidly increases as.

As shown in figure (4) The Time-Weighted Fourier Transform Analysis (TWFTA) is a powerful method used to study sound signals, particularly in dynamic environments where both time and frequency components need to be understood. This technique allows for a detailed examination of how sound waves evolve over time, revealing important frequency characteristics that might not be evident in traditional Fourier analysis. At lower flow rates, such as 120-210 L/min, sound signals tend to exhibit lower amplitudes and fewer high-frequency components. This is primarily because cavitation is minimal, and the fluid flow is more stable, leading to less turbulence. Consequently, the acoustic environment is quieter and more consistent, with fewer disturbances

Figure (5) shows that the flow rate increases to the 240-260 L/min range, more noticeable variations in sound amplitude can be detected. This is when cavitation may start to form, which results in greater noise levels and more irregular acoustic behavior. The developing cavitation introduces additional energy into the system, causing fluctuations in sound intensity

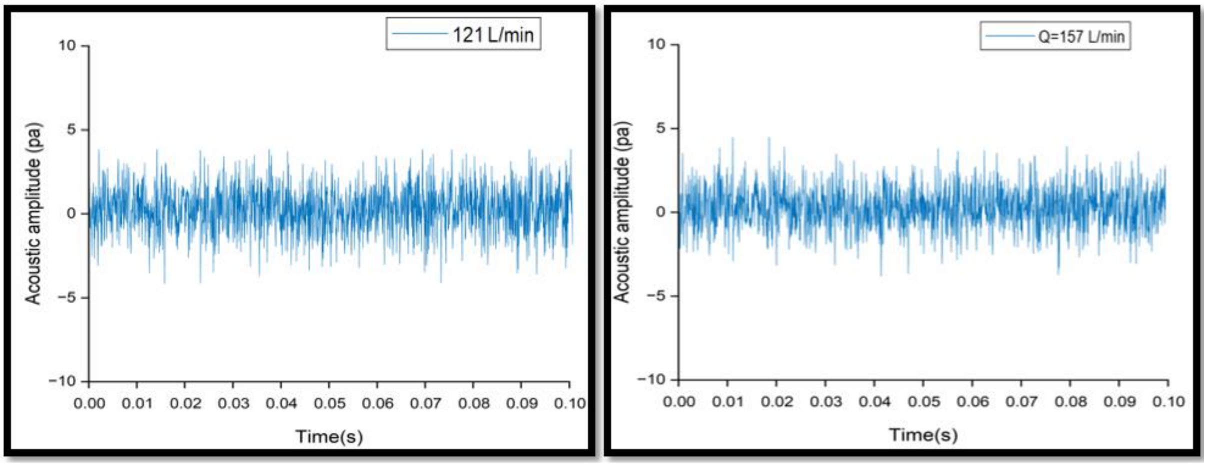


Figure 4. the sound wave in TWFTA at N=2765 rpm, No cavitation.

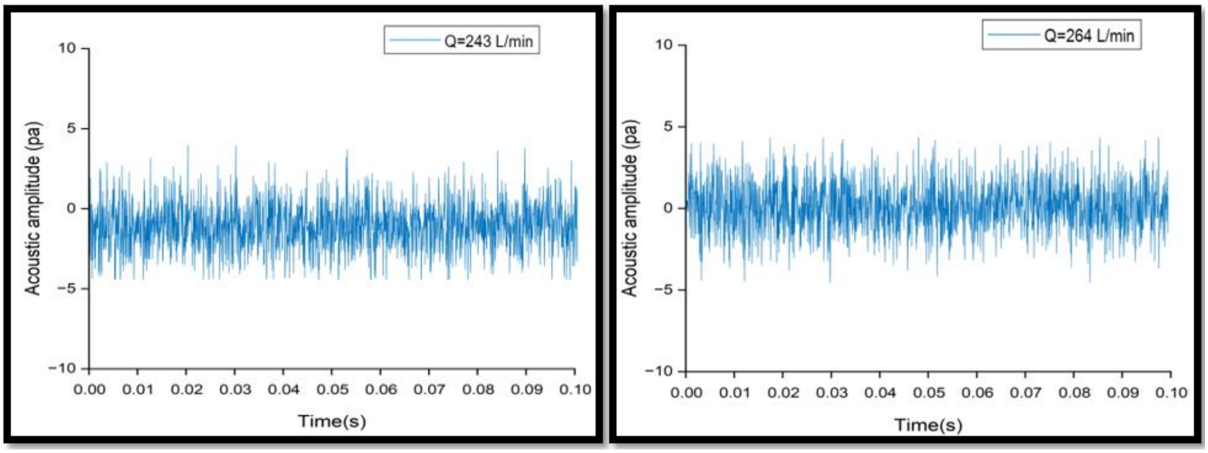


Figure 5. The sound wave in TWFTA at N=2765 rpm, inception of cavitation.

Figure (6) shows that at even higher flow rates, typically between 280-300 L/min, cavitation becomes much more severe. The sound waves grow in both intensity and variability, with significant increases in amplitude and the emergence of more pronounced high-frequency noise. The turbulent fluid movement and aggressive cavitation activity lead to a more chaotic sound profile, which is reflected in the higher energy present in the upper frequency spectrum.

Analysis of audio signals using a weighted time Fourier transform and evaluation of the characteristics (peak, peak-to-peak, square root, and variance) of cavitation detection in pumps: a comprehensive study of the acoustic effects caused by increased flow and cavitation evolution using statistical analysis of acoustic indicators, aimed at determining the optimal conditions for pump operation and minimizing the effects of cavitation on efficiency and performance, as shown in figure below The study compared with Liu et al. (2023)[20] found that low frequencies are the most sensitive for early detection of cavitation. However, the study added a detailed analysis of audio signals at low frequencies to understand different stages of cavitation and accurately determine starting points. It also added a statistical methodology to study peak values, RMS, and sound changes. Unlike Su et al. (2023)[21], the study focused on the effect of changes in flow on the intensity of sound signals. It added an analysis methodology based on the sensitivity of the audio signal at specific flow speeds (240-260 L/min).

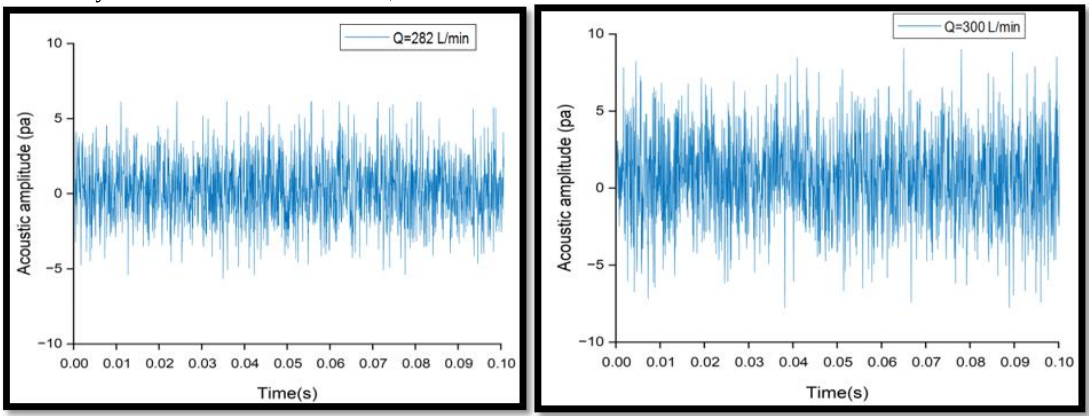
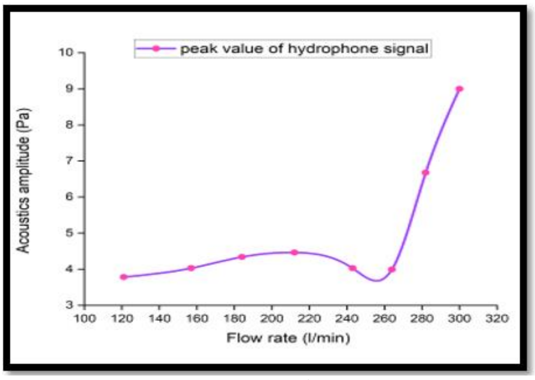
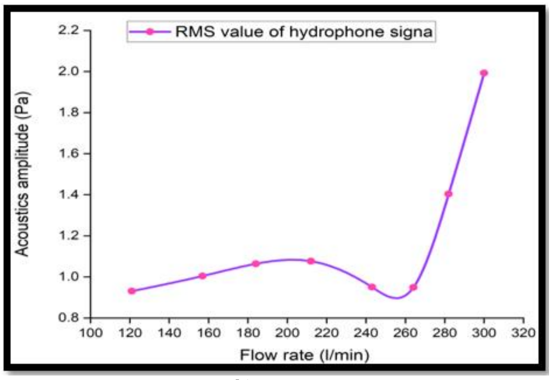


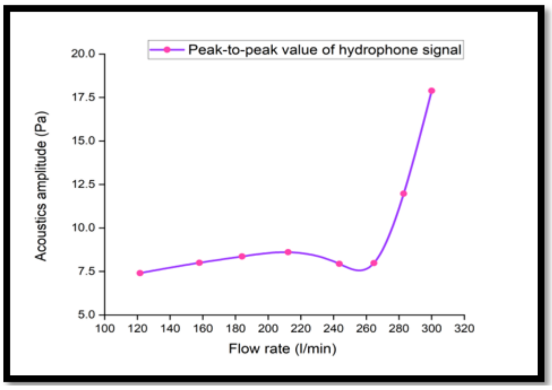
Figure 6. The sound wave inTWFTA at N=2765 rpmCavitation Development



a)



b)



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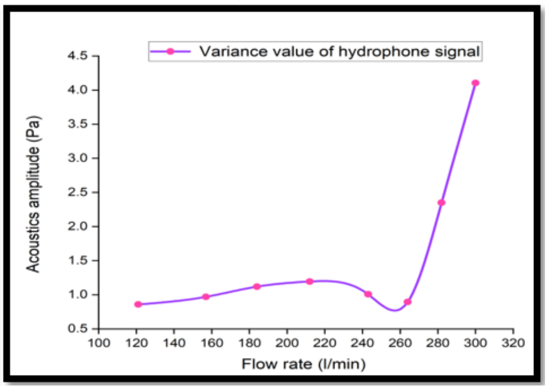

d)

Figure 7. characteristics the sound signal's peak, RMS, peak to peak, and variance at 2765rpm with flow rates variation.

Based on the time-domain acoustic analysis, the study reveals that acoustic signal analysis is an effective method for detecting and predicting cavitation in centrifugal pumps. The results indicate that additional hydraulic noise generated by internal recirculation at the discharge and suction zones leads to an increase in overall noise when the pump operates at flow rates higher than its designed capacity. When the flow rate is below 240 liters per minute (L/min), there is no significant change in the peak and RMS features of the acoustic signals as shown in figure (5-a, b). However, at flow rates exceeding 240 L/min, there is a rapid increase in acoustic wave amplitude. This suggests that cavitation conditions within the pump cause amplified and erratic trends in acoustic amplitude. Acoustic signals become effective predictors of cavitation effects, with peak values showing a more immediate increase compared to RMS characteristics. Among the time-domain features analyzed, peak-to-peak values exhibit greater sensitivity to cavitation than variance values. The study underscores the importance of peak and RMS features in predicting cavitation within the pump. Time-domain acoustic signal analysis enables the determination of both the pump's condition and the timing of cavitation events, providing valuable insights into pump performance and potential maintenance needs.An irregular trend (erratic trend) was observed at Flow rates ranging from 220 to 260 l/min, which was interpreted as a consequence of the onset of cavitation. When increasing the flow rate to the range 240-260 l / min, acoustic fluctuations become more pronounced, since the appearance of cavities leads to increased noise levels and irregular acoustic behavior. This behavior is caused by the introduction of additional energy into the system due to the collapse of the bubbles generated by the cavities figure (7.d) show (variation) of the sound intensity at each flow point. The diagram shows that the variability increases significantly at Flow rates between 240-260 l/min, reflecting the oscillations caused by the onset of the formation of cavities. This reinforces the hypothesis that cavities directly affect the behavior of the acoustic system

Figure (8) explains the compares the statistical properties of acoustic signals at different flow rates and pump rotational speeds. It was found that at a rotational speed of N=2765 rpm, the pump exhibited higher maximum peak values, increased RMS values, and larger minimum peak, RMS, peak-to-peak, and variance measurements compared to lower speeds of N=2625 rpm, 2335 rpm, and 2045 rpm. These results suggest that as the pumps rotational speed increases, so does the sound amplitude. This is due to intensified cavitation and impeller-volute interactions at higher speeds. The statistical features corresponding to various flow rates and rotational speeds are illustrated in the Figures provided,the study compares the findings of Mina L. Kellis et al. (2024) [22]and Xiaohui Liu et al. (2023)[20], who used vibration and noise signals to detect cavitation and analyze the effects of different speeds. The study found that an increase in rotation speed leads to a higher intensity of cavitation due to increased kinetic energy of bubbles and violent collapse. The study also used a hydrophone sensor to evaluate acoustic signals at different speeds (2045-2765 rpm), providing a more accurate understanding of cavitation dynamic changes. The study also compared with Calvin Stephen et al. (2024)[24], who focused on cavity detection using vibration techniques at different speeds in small pumps. The study expanded the analysis to the specifics of sound dynamics and determined cavitation levels based on changes in sound signals at specific speeds.

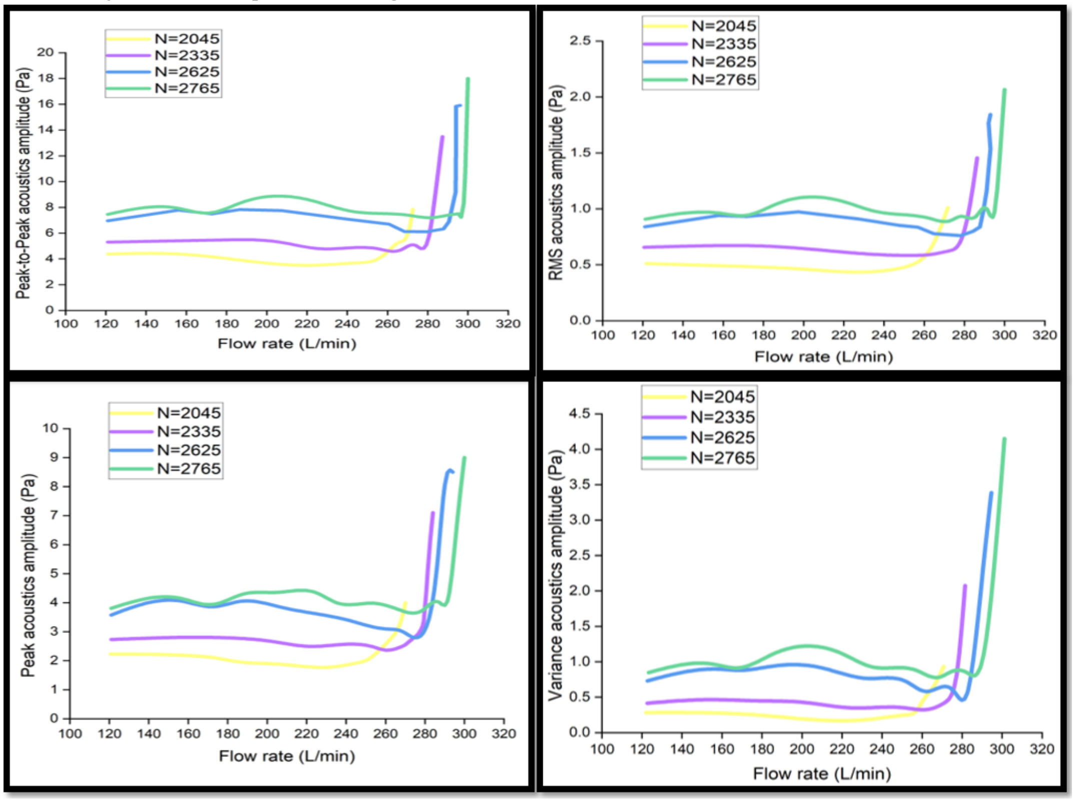

Figure 8. the peak,RMS,peak-to-peak, and variance of the acoustic signal at various rotational speeds.

Higher Rotational Speed (N=2765 rpm): data indicates that at higher speeds, the pump exhibits increased maximum peak features, RMS values, and larger minimum peaks, RMS, peak-to-peak, and variance values. This suggests a significant escalation in sound amplitude with rotational speed, reflecting greater cavitation activity. Lower speeds (N=2625 rpm, 2335 rpm, 2045 rpm) show reduced statistical metrics. This disparity underscores how increasing speed amplifies the acoustic signals associated with cavitation. The correlation between higher sound amplitude and increased rotational speed aligns with the phenomenon of cavitation. At elevated speeds, the interaction between the impeller and volute becomes more pronounced, leading to enhanced cavitation effects. As speed rises, the formation and collapse of vapor bubbles become more severe. The bubbles disrupt the fluid flow, leading to increased hydraulic losses and reduced efficiency. The collapse of these bubbles can cause significant damage to pump components, including erosion and pitting. The disruption in fluid flow and the increase in hydraulic losses result in decreased pump efficiency. This is a direct consequence of intensified cavitation, which hampers the pump's ability to operate optimally. The physical damage to the impeller and volute due to repeated cavitation can lead to long-term operational issues. This includes erosion, pitting, and potential failure of critical components.

6. Conclusions

The study revealed that acoustic signals can effectively predict cavitation within a pump. Various statistical features in the time domain, such as peak, root mean square (RMS), peak-to-peak, and variance values, were identified as useful metrics for assessing and detecting cavitation from acoustic signals.Extensive testing was conducted to understand the impact of different flow rates on pump cavitation. The study categorized cavitation into four distinct levels based on flow rates:

1. **No Cavitation**: Observed at flow rates between 120 and 210 liters per minute (L/min).
2. **Gradual Cavitation**: Detected at flow rates between 240 and 260 L/min.
3. **Developing Cavitation**: Present at flow rates between 260 and 280 L/min.
4. **Full Cavitation Development**: Occurred at flow rates exceeding 280 L/min.

High vapor volume fractions near the impeller inlet were found to cause significant performance degradation. These high vapor volumes obstructed water flow, leading to reduced pump efficiency. The alteration in acoustic waves was attributed to the cavitation process and the intense interaction between the impeller and volute.

Furthermore, the study established a direct correlation between acoustic amplitude and pump flow rate. As the flow rate increased, the acoustic amplitude also increased, reflecting the intensity of cavitation and its impact on the pump's operation.

REFRENCES

[1] D. B. Jani, M. Yash, S. Mit, S. Ajay, S. Jeel, and P. Pritesh, "An overview on cavitation in centrifugal pump," *Int. J. Innov. Res. Technol.*, vol. 6, no. 5, pp. 15–19, 2019, [Online]. Available: https://www.researchgate.net/publication/336253916

[2] N. Kundu and A. Preetham, "Optimization and Cavitation Analysis of Centrifugal Pump with Variable Working Parameters Using Ansys CFX".

[3] Z. Tong, H. Liu, X. E. Cao, D. Westerdahld, and X. Jin, "Cavitation diagnosis for water distribution pumps: An early-stage approach combing vibration signal-based neural network with high-speed photography," *Sustain. Energy Technol. Assessments*, vol. 55, 2023, doi: 10.1016/j.seta.2022.102919.

[4] S. M. Jafari and N. Malekjani, "Transporting Operations of Food Materials within Food Factories: Unit Operations and Processing Equipment in the Food Industry," *Transp. Oper. Food Mater. within Food Factories Unit Oper. Process. Equip. Food Ind.*, pp. 1–381, 2022, doi: 10.1016/C2018-0-04496-5.

[5] S. K. Aithal, N. R. Babu, H. N. Manjunath, and K. S. Chethan, "Characterization of Al-SiCP Functionally Graded Metal Matrix Composites Developed through Centrifuge Casting Technique," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 15, no. 5, pp. 483–490, 2021.

[6] Y. Liu, X. Ren, and C. Dong, "Transmission performance analysis of non-circular gear hydraulic motor," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 18, no. 3, pp. 635–644, 2024, doi: 10.59038/jjmie/180316.

[7] M. Karagiovanidis, X. E. Pantazi, D. Papamichail, and V. Fragos, "Early Detection of Cavitation in Centrifugal Pumps Using Low-Cost Vibration and Sound Sensors," *Agric.*, vol. 13, no. 8, 2023, doi: 10.3390/agriculture13081544.

[8] SubektiSubekti, HarusLaksanaGuntur, V. S. Djanali, and AchmadSyaifudin, "Identification of Nonlinear System for Elastically Supported Cylinder on Cross-Flow Using Wavelet Transform," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 18, no. 1, pp. 89–97, 2024, doi: 10.59038/jjmie/180107.

[9] G. Mousmoulis, C. Yiakopoulos, G. Aggidis, I. Antoniadis, and I. Anagnostopoulos, "Application of Spectral Kurtosis on vibration signals for the detection of cavitation in centrifugal pumps," *Appl. Acoust.*, vol. 182, p. 108289, 2021, doi: 10.1016/j.apacoust.2021.108289.

[10] A. P. Irawan *et al.*, "Influence of Post-Heat Treatment on the Characteristics of FeCrBMnSi Coating on Stainless Steel 304 Substrate Prepared by Twin Wire Arc Spray (TWAS) Method at Various Stand-off Distance," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 18, no. 2, pp. 327–337, 2024, doi: 10.59038/jjmie/180206.

[11] S. A. Abdollahi, M. Nami, and F. Ranjbar, "empirical methods of diagnose of cavitation and impact of vibration caused by cavitation on centrifugal pumps empirical methods of diagnose of cavitation and impact of vibration caused by cavitation on centrifugal pumps," no. May, 2023.

[12] L. Li *et al.*, "Effect of surface damage induced by cavitation erosion on pitting and passive behaviors of 304L stainless steel," *Int. J. Miner. Metall. Mater.*, vol. 30, no. 7, pp. 1338–1352, 2023, doi: 10.1007/s12613-023-2602-0.

[13] A. R. Al-Obaidi, "Experimental Diagnostic of Cavitation Flow in the Centrifugal Pump Under Various Impeller Speeds Based on Acoustic Analysis Method," *Arch. Acoust.*, vol. 48, no. 2, pp. 159–170, 2023, doi: 10.24425/aoa.2023.145234.

[14] L. Dong, Y. Zhao, and C. Dai, "Detection of inception cavitation in centrifugal pump by fluid-borne noise

diagnostic," *Shock Vib.*, vol. 2019, 2019, doi: 10.1155/2019/9641478.

[15] T. Alsardia and L. Lovas, "Investigation of the Effect of the Surface Treatment and Lubrication During Repeated Tightening on the Nut Coefficient of a Bolted Joint Using the Taguchi Method," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 18, no. 1, pp. 131–144, 2024, doi: 10.59038/jjmie/180110.

[16] B. H. Al khaqani and N. M. Dawood, "Control Degradation of New Magnesium Alloy by MgF2 Coating for Cardiovascular Applications," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 18, no. 2, pp. 391–400, 2024, doi: 10.59038/jjmie/180211.

[17] H. S. Majdi, L. J. Habeeb, J. M. Hadi, and D. Zivkovic, "A 3D CFD simulation of cavitation phenomena for a centrifugal pump with multi rotational speed and pressure," *Int. J. Mech. Eng.*, vol. 7, no. 1, pp. 796–809, 2022.

[18] Q. Si *et al.*, "Assessment of cavitation noise in a centrifugal pump using acoustic finite element method and spherical cavity radiation theory," *Eng. Appl. Comput. Fluid Mech.*, vol. 17, no. 1, 2023, doi: 10.1080/19942060.2023.2173302.

[19] A. K. Jaiswal, A. U. Rehman, A. R. Paul, and A. Jain, "Detection of cavitation through acoustic generation in centrifugal pump impeller," *J. Appl. Fluid Mech.*, vol. 12, no. 4, pp. 1103–1113, 2019, doi: 10.29252/jafm.12.04.29501.

[20] X. Liu, J. Mou, X. Xu, Z. Qiu, and B. Dong, "A Review of Pump Cavitation Fault Detection Methods Based on Different Signals," *Processes*, vol. 11, no. 7, 2023, doi: 10.3390/pr11072007.

[21] W. Su, W. Meng, Y. Zhao, J. Wu, and Y. Sun, "Research on an acoustic judgment method for the incipient cavitation of model hydraulic machinery runner blades," *Rev. Mater.*, vol. 28, no. 3, 2023, doi: 10.1590/1517-7076-RMAT-2023-0154.

[22] M. Kerellous, T. Mekhail, W. Abdel-FadEel, and H. Abdel-mohsen, "Experimental and Numerical Study of Cavitation Phenomenon in a Semi-open Impeller Centrifugal Pump," *Int. J. Appl. Energy Syst.*, vol. 6, no. 1, pp. 23–36, 2024, doi: 10.21608/ijaes.2023.210084.1017.

[23] J. Fernandes, P. J. Ramísio, and H. Puga, "Unveiling Acoustic Cavitation Characterization in Opaque Chambers through a Low-Cost Piezoelectric Sensor Approach," *Electron.*, vol. 13, no. 8, pp. 1–14, 2024, doi: 10.3390/electronics13081581.

[24] C. Stephen, B. Basu, and A. McNabola, "Detection of Cavitation in a Centrifugal Pump-as-Turbine Using Time-Domain-Based Analysis of Vibration Signals," *Energies* , vol. 17, no. 11, 2024, doi: 10.3390/en17112598.

[25] "Lowara CEA 210/2/D-V Single-impeller pump (104480050XAA)." Accessed: Sep. 04, 2024. [Online]. Available: https://www.lenntech.com/products/Lowara-CEA/104480050XAA/210/2/D-V-Single-impeller-pump/index.html

[26] "ASF-1 MKII - Hydrophone w/ 48V-Phantom Power Supply – Ambient Webshop." Accessed: Sep. 04, 2024. [Online]. Available: https://ambient.de/en/products/asf-1-mkii-hydrophone-mit-48v-phantomspeisung

[27] G. Mousmoulis, I. Kassanos, G. Aggidis, and I. Anagnostopoulos, "Numerical simulation of the performance of a centrifugal pump with a semi-open impeller under normal and cavitating conditions," *Appl. Math. Model.*, vol. 89, pp. 1814–1834, 2021, doi: 10.1016/j.apm.2020.08.074.

[28] M. Song, Y. Zhi, M. An, W. Xu, G. Li, and X. Wang, "Centrifugal Pump Cavitation Fault Diagnosis Based on Feature-Level Multi-Source Information Fusion," *Processes*, vol. 12, no. 1, 2024, doi: 10.3390/pr12010196.

[29] D. Liang, Z. Yuqi, D. Cui, and W. Yong, "Research on cavitation acoustic characteristics of centrifugal pump based on fluid-acoustic field coupling method," *Adv. Mech. Eng.*, vol. 10, no. 5, pp. 1–13, 2018, doi: 10.1177/1687814018773665.

[30] J. Lu, X. Liu, Y. Zeng, B. Zhu, B. Hu, and H. Hua, "Investigation of the noise induced by unstable flow in a centrifugal pump," *Energies*, vol. 13, no. 3, 2020, doi: 10.3390/en13030589.

[31] A. Berkane, M. Aksas, and Z. Aouachria, "Performance Study of a Hybrid Solar-Assisted Ground-Source Heat Pump System Used for Building Heating and Hot Water Demands," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 17, no. 4, pp. 581–594, 2023, doi: 10.59038/jjmie/170413.

[32] Y. Wei, Y. Shi, W. Shi, and B. Pan, "Numerical Analysis and Experimental Study of Unsteady Flow Characteristics in an Ultra-Low Specific Speed Centrifugal Pump," *Sustain.*, vol. 14, no. 24, 2022, doi: 10.3390/su142416909.

[33] A. K. Azad, M. F. Saffiudeen, A. Syed, and F. T. Mohammed, "Fabrication of Al-6061/SiC Nano Composite Material Through Ultrasonic Cavitation Technique and Its Analysis," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 17, no. 3, pp. 319–326, 2023, doi: 10.59038/jjmie/170301.

[34] E. B. Maxime Binama, Alex Muhirwa, "Cavitation effects in centrifugal pumps- A review," *Int. J. Eng. Res. Appl.*, vol. 6, no. 5, pp. 52–63, 2016.

[35] Lara, "Numerical simulations of cavitation in the oil pump and thin-fluid-bearing for automotive applications," *הארץ*, no. 8.5.2017, pp. 2003–2005, 2022, [Online]. Available: www.aging-us.com