

## Vibration Based Fault Analysis of a Centrifugal Cooling Water Pump Using FFT and Pressure Parameters

**Muhammad Dicky Agus Prawira, Harus Laksana Guntur\***

Institut Teknologi Sepuluh Nopember, Indonesia

Email: 6007241010@student.its.ac.id\*

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centrifugal pump; cavitation; FFT analysis; vibration spectrum; suction pressure

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**Abstract**

Centrifugal pumps in cooling water systems play an important role in maintaining operational stability in the pulp and paper industry. However, vibration often affects these pumps due to hydraulic and mechanical irregularities. This research identifies vibration characteristics in a centrifugal pump using FFT based spectrum analysis. This technique converts time-domain signals into frequency components. The analysis is complemented by suction pressure evaluation to better describe operating conditions. Vibration measurements were carried out using an SKF Vibrometer at six points on the Drive End (DE) and Non-Drive End (NDE) in horizontal, vertical, and axial directions. The results show abnormal conditions at all locations. Vibration velocity reached 10.73 mm/s, which exceeds the ISO 10816 alert (2.80 mm/s) and danger (4.50 mm/s) limits. The suction pressure was recorded at -0.3 bar, indicating a significant inlet pressure drop. The FFT spectrum reveals a dominant  $1 \times$  RPM component. This is typically associated with rotor unbalance. The spectrum also shows indications of misalignment or looseness from multi-directional vibration. In addition, broadband energy in the mid- to high-frequency range and a clear spectral "hump" indicate unstable, non-periodic excitation. Mechanical faults may contribute, but several findings stand out. The combination of broadband energy, spectral hump, and low suction pressure strongly suggests cavitation as the dominant fault mechanism. Cavitation occurs when vapor bubbles form and collapse due to insufficient inlet pressure. This process generates a wideband vibration. Integrating FFT-based vibration analysis with pressure data improves fault identification accuracy. This approach provides a reliable framework for centrifugal pump condition monitoring.

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### INTRODUCTION

The pulp and paper industry is a manufacturing sector with high utility demands, where HVAC systems play a critical role in maintaining stable temperatures and humidity throughout production processes. System performance depends on the effectiveness of the chillers and centrifugal pumps that circulate cooling water from the cooling tower to the condenser (Gülich, 2019).

Centrifugal pumps ensure continuous fluid circulation. Their performance depends on both mechanical and hydraulic conditions. Various faults may occur during operation, such as unbalance, misalignment, and looseness (Kumar et al., 2023; Tiboni et al., 2022). Hydraulic phenomena, including cavitation, also affect performance, each producing distinct vibration characteristics (Arun et al., 2020). Vibration analysis in the frequency domain is widely used to identify these faults by their spectral patterns (Garousi et al., 2024).

According to International Organization for Standardization, (2009), vibration is a key indicator of rotating machinery condition, where excessive vibration levels indicate potential

mechanical failure. Therefore, vibration monitoring plays an important role in predictive maintenance strategies to minimize downtime and prevent unexpected failures (Atassi & Alhosban, 2023; Romanssini et al., 2023; Shah et al., 2025). In vibration-based diagnosis, mechanical faults such as unbalance typically produce a dominant peak at  $1\times$  rotational frequency, while misalignment generates multiple harmonics ( $1\times$ ,  $2\times$ , and higher).

In addition to mechanical faults, hydraulic phenomena such as cavitation significantly affect pump performance and vibration behaviour. Cavitation occurs when the local pressure drops below the fluid's vapor pressure, leading to the formation and collapse of vapor bubbles that generate broadband, high-frequency vibration and noise (Sun et al., 2026). Previous studies have shown that cavitation increases vibration amplitude and alters frequency characteristics under different operating conditions (Li et al., 2022; Zhang et al., 2017). Experimental investigations have also demonstrated that vibration and acoustic signals can be used to detect cavitation; however, these approaches often lack integration with direct pressure measurements (Al-Obaidi, 2023).

Several studies have demonstrated the effectiveness of FFT-based vibration analysis for fault diagnosis. Singh and Hassan, (2025) applied FFT to identify mechanical faults in centrifugal pumps, while Fajar and Widodo, (2016) as well as Sun et al. (2026), analyzed cavitation characteristics using vibration signals. Furthermore, recent research has explored advanced signal processing techniques to improve diagnostic accuracy. For example, Liu and Yan, (2019) proposed a sparse representation-based method for extracting fault features from vibration signals under noisy conditions. Despite these advancements, most studies focus on vibration analysis or hydraulic effects separately, without integrating both.



**Figure 1.** Direct measurement data

Source: Initial field measurement at PT Indah Kiat Pulp & Paper Tbk., Karawang Unit, June 2025

This issue was identified in four centrifugal pumps in the cooling water system at PT. Indah Kiat Pulp & Paper Tbk., Karawang, following utility commissioning in June 2025. Field observations revealed abnormal operating conditions, including high noise levels and negative suction pressure. Pressure measurements recorded  $-0.3$  bar ( $-30$  kPa), indicating a significant pressure drop that may approach or fall below the fluid's vapor pressure. Under such conditions, cavitation may occur, leading to increased vibration, potential damage, and efficiency loss (Gulich, 2019). Initial vibration measurements showed a high level of  $7.2$  mm/s; however, they provided only overall values, without the frequency-domain characteristics required for accurate fault identification.

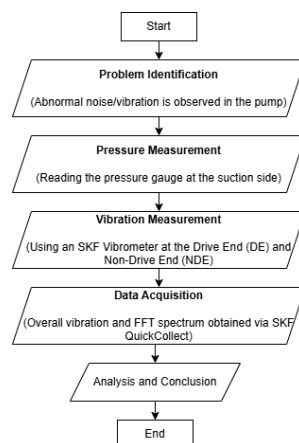
As shown in Figure 1, the initial measurements consist of both vibration and suction pressure results. The vibration data are presented only as overall numerical values without FFT spectrum visualization, limiting the ability to identify specific fault characteristics. Meanwhile, the suction pressure measurement indicates a negative pressure condition at the pump inlet. Therefore, in this study, further vibration analysis will be conducted using measurement tools equipped with Fast Fourier Transform (FFT) capabilities to obtain detailed frequency-domain information for more accurate fault diagnosis.

To overcome this limitation, further measurements using Fast Fourier Transform (FFT) are necessary to analyze vibration spectra in detail. However, relying solely on vibration analysis may lead to ambiguity in distinguishing between mechanical faults and hydraulic-induced cavitation.

Therefore, based on the identified gap, the main research question of this study is: How can FFT-based vibration spectrum analysis be integrated with suction pressure parameters to accurately distinguish between mechanical faults and cavitation in centrifugal pumps?

Accordingly, the objective of this study is to develop an integrated diagnostic approach combining FFT-based vibration spectrum analysis with suction pressure parameters. By correlating vibration characteristics with pressure conditions, this approach aims to improve fault-identification accuracy and to provide more reliable differentiation between mechanical faults and hydraulic phenomena in centrifugal pump systems. This research is expected to provide benefits, both theoretically and practically. Theoretically, this research contributes to the development of science in the field of predictive maintenance engineering and the diagnosis of centrifugal pump malfunctions, in particular in the integration of FFT-based vibration spectrum analysis with suction pressure parameters to accurately distinguish between mechanical faults and hydraulic phenomena such as cavitation. Practically, this research is useful for maintenance technicians and engineers in the pulp and paper industry as a guide in implementing more accurate and efficient condition monitoring strategies; for plant management in making more timely machine maintenance decisions thereby reducing downtime and repair costs; and for future researchers as a reference in the development of more integrated and reliable centrifugal pump damage diagnosis methods.

## METHOD



**Figure 2.** Research Flow

Source: Author's own work, 2026

The research process began with problem identification, where abnormal noise and vibration were observed in the centrifugal pump during operation, indicating potential mechanical or hydraulic issues requiring further investigation.

Subsequently, pressure measurements were conducted using a pressure gauge installed on the suction side of the pump to evaluate hydraulic conditions, particularly to detect negative pressure that may indicate cavitation.

Vibration measurements were then performed using an SKF Vibrometer at critical locations, namely the Drive End (DE) and Non-Drive End (NDE), to capture vibration behaviour from different structural points. Measurements were taken in horizontal, vertical, and axial directions.

Data acquisition was carried out by collecting overall vibration values and FFT (Fast Fourier Transform) spectra using the SKF QuickCollect application. This process provided detailed information on vibration characteristics in both time and frequency domains.

Finally, the collected data were analyzed by interpreting vibration patterns and correlating them with pressure data to identify the root cause of the problem. Based on this analysis, conclusions were drawn regarding the pump condition and the dominant vibration source, whether mechanical or hydraulic.

This study was conducted at PT Indah Kiat Pulp & Paper Tbk., Karawang Unit, West Java, focusing on the cooling water pump system, which consists of four identical centrifugal pump units. However, the scope of this research was limited to one unit, namely pump U2053.

The pump used in this study is a centrifugal pump manufactured by Andritz China, type ACP300-400.3F DD. The pump has a flow rate of 1250 m<sup>3</sup>/h, a head of 30 m, and is driven by a 160-kW motor operating at 1485 rpm. The impeller diameter is Ø 386/70 mm, and the unit was manufactured in 2024.

**Table 1.** Specifications Pump

Parameter	Value
Flow Rate (Q)	1250 m <sup>3</sup> /h
Motor Power (P)	160 kW
Head (H)	30 m
Rotational Speed (n)	1485 rpm
Impeller Diameter	Ø 386/70 mm
Year of Manufacture	2024

Source: PT Indah Kiat Pulp & Paper Tbk., Karawang Unit (manufacturer datasheet, 2024)



**Figure 2.** Centrifugal Pump

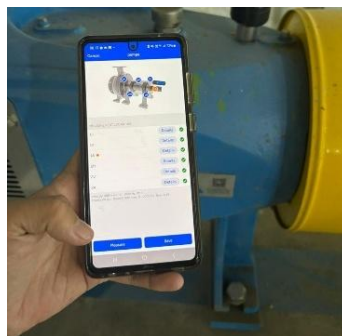
Source: Documentation of research, PT Indah Kiat Pulp & Paper Tbk., Karawang Unit, 2026

### Measurements Point

As illustrated in Figure 3, the measurement points represent the locations for vibration data acquisition on the centrifugal pump using an SKF Vibrometer.

Vibration measurements in this study were conducted using an SKF Vibrometer, a portable instrument designed for rapid and accurate condition monitoring of rotating machine. The device is equipped with an integrated sensor that measures vibration parameters, including velocity (mm/s), acceleration, and frequency spectrum, making it suitable for both overall evaluation and detailed fault diagnosis during the measurement process, the vibrometer was positioned at predefined locations, namely the Drive End (DE) and Non-Drive End (NDE), and measurements were taken in the horizontal, vertical, and axial directions. The acquired vibration signals were processed using the Fast Fourier Transform (FFT) to convert time-domain data to the frequency domain, enabling the identification of characteristic vibration patterns associated with faults such as unbalance, misalignment, and cavitation.

The measurement results were displayed using the SKF QuickCollect application, connected via Bluetooth, as shown in Figure 4. The application provides overall vibration values and FFT-based spectra, and supports real-time monitoring, data storage, and trend analysis. Therefore, integrating the SKF Vibrometer and the SKF QuickCollect application provides an efficient and reliable approach for vibration data acquisition and analysis, enhancing the accuracy of fault identification in centrifugal pumps within a predictive maintenance framework.



**Figure 3.** SKF Quick Collect application

Source: SKF Group, QuickCollect Application User Manual, 2024; screenshot captured during research, 2026





**Figure 4.** Measurement Point

Source: Documentation of research, PT Indah Kiat Pulp & Paper Tbk., Karawang Unit, 2026

In addition to vibration measurements, this study utilizes pressure data obtained from a pressure gauge installed on the suction side of the pump, as shown in Figure 5. The gauge measures fluid pressure to evaluate hydraulic conditions, particularly to detect negative pressure that may trigger cavitation.

The recorded data indicate negative suction pressure, representing a pressure drop below atmospheric conditions. This condition is critical, as it may lead to vapor bubble formation when the local pressure approaches or falls below the fluid's vapor pressure.

Furthermore, the pressure data are correlated with vibration data obtained from the SKF Vibrometer to provide a more comprehensive evaluation of pump performance. This integrated analysis enables vibration patterns observed in the FFT spectrum to be interpreted in relation to hydraulic conditions. For instance, an increase in broadband high-frequency vibration accompanied by negative suction pressure indicates cavitation rather than purely mechanical faults such as unbalance or misalignment.

Therefore, integrating vibration and pressure data enhances fault diagnosis accuracy by linking mechanical responses to underlying hydraulic phenomena in the centrifugal pump system.



**Figure 5.** Pressure Gauge Position

Source: Documentation of research, PT Indah Kiat Pulp & Paper Tbk., Karawang Unit, 2026

## **Vibration Data Processing**

The vibration parameters analyzed in this study include vibration velocity (mm/s) and the frequency spectrum obtained from Fast Fourier Transform (FFT) analysis. The vibration velocity is evaluated as the root mean square (RMS) value measured in three directions (horizontal, vertical, and axial) at each measurement point. The average vibration value is then determined by calculating the mean of these directional measurements, which represents the overall vibration condition of the machine and enables comparison across different measurement locations and operating conditions.

The calculated vibration velocity is subsequently used to determine the severity level of the machine condition according to ISO 10816-3, which classifies conditions into categories ranging from good to unacceptable. This standard is widely used for evaluating the operational condition of rotating machinery based on vibration severity levels.

## **Fault Diagnosis Method**

Fault diagnosis in this study is performed by analyzing the vibration frequency spectrum obtained from Fast Fourier Transform (FFT). Each type of mechanical and hydraulic fault exhibits distinct spectral characteristics that can be identified through dominant frequency patterns and energy distribution in the spectrum. Based on established vibration analysis practices and guidelines, machine faults can be distinguished by spectral signatures, including discrete peaks and broadband frequency components.

The diagnostic criteria applied in this study are summarized as follows:

### **Unbalance**

Characterized by a dominant peak at  $1\times$  rotational frequency with minimal harmonic components.

### **Misalignment**

Indicated by peaks at  $1\times$  and  $2\times$  rotational frequencies, often accompanied by higher harmonics depending on severity.

### **Looseness**

Identified by multiple harmonics and irregular spectral patterns due to mechanical looseness in machine components.

### **Cavitation:**

Characterized by broadband high-frequency vibration and elevated noise levels caused by the random collapse of vapor bubbles, typically appearing as a spectral “hump” rather than distinct peaks (Randall, 2011).

Furthermore, the shaft rotational frequency is determined from the pump rotational speed and serves as a reference to identify harmonic components, such as  $1\times$ ,  $2\times$ , and higher-order frequencies, in the FFT spectrum. This approach is widely applied in vibration-based condition monitoring and fault diagnosis of rotating machinery.

## **Integrated Vibration and Pressure Analysis**

To enhance diagnostic accuracy, vibration analysis results are correlated with suction pressure measurements to evaluate both mechanical and hydraulic operating conditions of the pump. Variations in suction pressure are analyzed alongside vibration characteristics in the FFT spectrum, where broadband high-frequency components indicate abnormal operating conditions.

This integrated approach enables clear differentiation between vibration sources associated with mechanical faults, such as unbalance and misalignment, and those associated with hydraulic phenomena, such as cavitation. By combining vibration and pressure-based indicators, a more comprehensive understanding of pump behaviour under real operating conditions can be achieved.

In addition, suction-side pressure is evaluated using the Net Positive Suction Head (NPSH) concept, where a reduction in Net Positive Suction Head Available (NPSH<sub>a</sub>) may indicate unfavourable hydraulic conditions that increase the likelihood of cavitation occurrence.

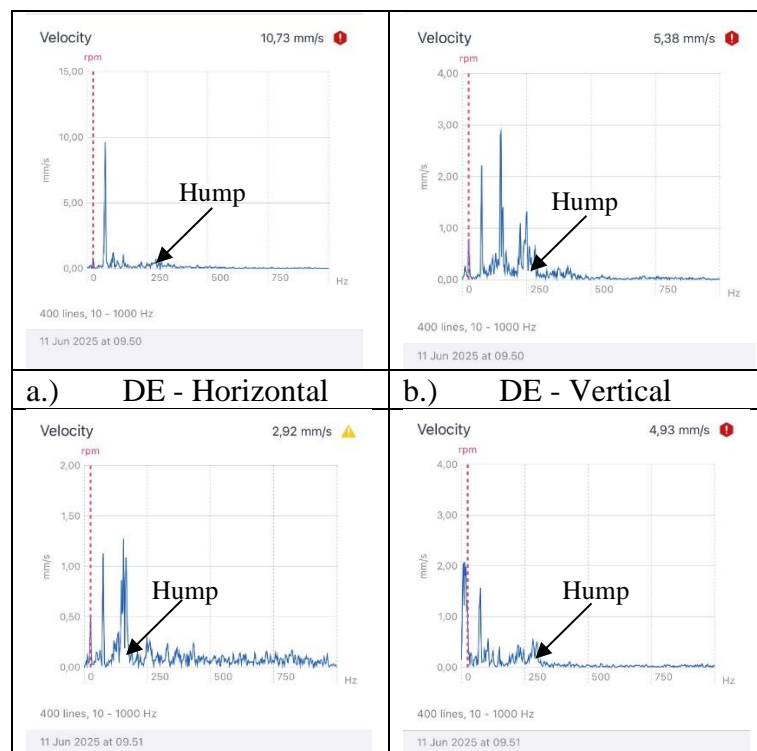
## RESULTS AND DISCUSSION

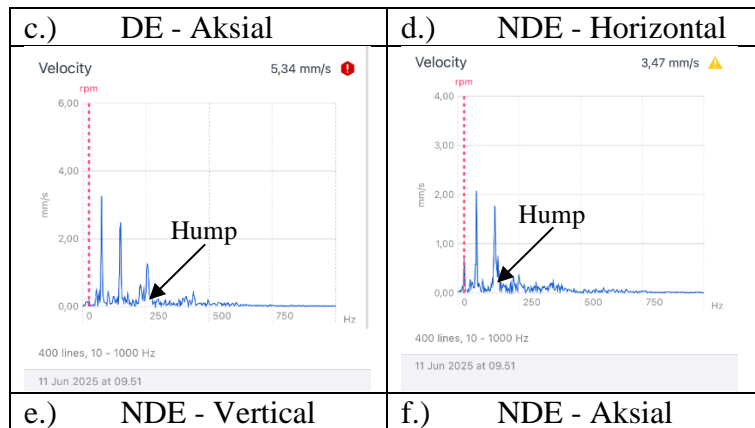
The vibration measurement results at the six observation points are presented in Table 2 and Figure 6. Table 2 summarizes the vibration velocity values along with their corresponding condition classifications, while Figure 6 illustrates the associated frequency spectra obtained from FFT analysis.

As shown in Figure 6, all measurement points exhibit similar spectral characteristics. The vibration velocity values at all points exceed the limits defined in ISO 10816-3, namely 2.80 mm/s (alert) and 4.50 mm/s (danger), indicating that the pump operates under abnormal conditions with a high potential for severe mechanical or hydraulic faults.

The consistent spectral patterns across all measurement points suggest that the vibration phenomenon is not localized but rather system-wide. This indicates the presence of a dominant excitation source affecting the overall dynamic behavior of the pump system.

The combined evaluation of vibration amplitude and frequency spectrum provides both quantitative and qualitative insights, forming a strong basis for further analysis to identify the dominant vibration mechanism and fault type within the system.





**Figure 6.** Result check vibration

Source: Vibration measurement results processed using SKF QuickCollect application, 2026

**Tabel 2.** Value and Status vibration

Point	Value (mm/s)	Status
DE-Horizontal	10.73	Danger
DE-Vertical	5.38	Danger
DE-Aksial	2.92	Alert
NDE-Horizontal	4.93	Danger
NDE-Vertical	5.34	Danger
NDE-Aksial	3.47	Alert

Source: Vibration measurement results at DE and NDE points, processed by author, 2026

## FFT spectrum analysis for fault diagnosis

### Fault Diagnosis DE

Based on Table 2, the highest vibration velocity at the Drive End (DE) is observed in the horizontal direction at 10.73 mm/s (danger), followed by the vertical direction at 5.38 mm/s (danger) and the axial direction at 2.92 mm/s (alert). The elevated vibration levels in the radial directions indicate a significant abnormal operating condition.

Correlation with the FFT spectra in Figures 6 (a)–(c) shows that, in addition to the dominant peak at  $1\times$  rotational frequency, there is a noticeable increase in broadband energy forming a hump in the mid- to high-frequency range. This pattern is most prominent in Figure 6(a) (DE-Horizontal), which shows the highest vibration value, followed by lower intensity in Figure 6(b) (DE-Vertical), while Figure 6(c) (DE-Axial) exhibits more distributed energy with lower amplitude.

These spectral characteristics are indicative of cavitation, where the formation and collapse of vapor bubbles generate random broadband vibration, in contrast to discrete peaks typically associated with mechanical faults such as unbalance or misalignment [11], [9].

Therefore, based on the vibration severity and FFT spectral patterns, it can be concluded that the pump at the Drive End (DE) is experiencing developed cavitation.

### Fault Diagnosis NDE

Based on Table 2, the vibration velocity at the Non-Drive End (NDE) indicates abnormal operating conditions, with values of 4.93 mm/s (horizontal) and 5.34 mm/s (vertical), both classified as danger, while the axial direction shows 3.47 mm/s (alert). The elevated

vibration levels, particularly in the radial directions, indicate a significant disturbance in the pump system.

Referring to the FFT spectra in Figures 6 (d)–(f), the vibration signals exhibit not only a dominant peak at the rotational frequency ( $1\times$  RPM) but also broadband energy forming a hump in the mid-frequency range. This pattern is evident in Figure 6(d) (NDE-Horizontal) and becomes more pronounced in Figure 6(e) (NDE-Vertical), consistent with the highest vibration value. Figure 6(f) (NDE-Axial) shows a more distributed spectrum with lower amplitude, yet it still indicates non-discrete vibration energy.

These spectral characteristics are indicative of cavitation, in which the formation and collapse of vapor bubbles generate random broadband vibration, in contrast to the discrete harmonic peaks typically associated with mechanical faults.

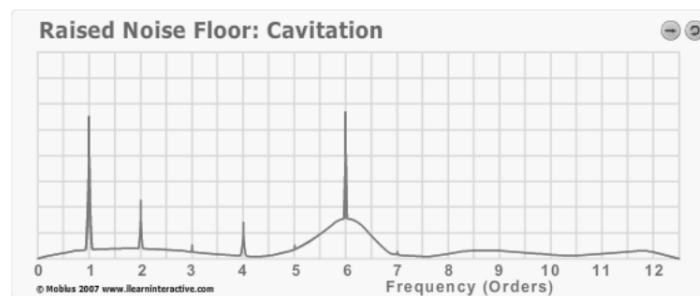
Therefore, based on the vibration severity levels and FFT spectral patterns, it can be concluded that the pump at the Non-Drive End (NDE) is also experiencing developed cavitation. The consistent occurrence at both DE and NDE indicates that the vibration source affects the system as a whole.

### DE and NDE

Based on vibration measurement results at the Drive End (DE) and Non-Drive End (NDE), most measurement points fall into the danger category, particularly in the radial direction, indicating abnormal operating conditions.

The FFT spectra at all measurement points (Figure 6 a–f) show a broadband energy forming a characteristic “hump” in the mid- to high-frequency range. This spectral pattern is not typical of mechanical faults such as unbalance or misalignment, but is more consistent with cavitation characteristics.

Therefore, it can be concluded that the pump is experiencing fully developed cavitation across the system, which is associated with hydraulic conditions such as low suction pressure or insufficient Net Positive Suction Head (NPSH).



**Figure 7.** Mobius Institute Quick Reference Guide

Source: Mobius Institute, Vibration Analysis Quick Reference Guide, 2019; reproduced for educational purposes

Based on the FFT spectral analysis at both the Drive End (DE) and Non-Drive End (NDE), the vibration patterns exhibit consistent characteristics across all measurement points. When compared with the reference spectrum in Figure 7, adapted from established vibration analysis guidelines, a similar broadband energy distribution is observed, accompanied by a characteristic hump in the mid- to high-frequency range.

This spectral signature is typically associated with cavitation phenomena rather than mechanical faults such as unbalance or misalignment, which are generally characterized by distinct harmonic peaks at specific multiples of the rotational frequency. The presence of broadband high-frequency content further supports the occurrence of hydraulic instability, driven by vapor bubble formation and collapse within the pump.

The agreement between the measured FFT results and the reference spectral pattern confirms the reliability of the diagnostic approach used in this study and strengthens the identification of cavitation as the dominant fault mechanism in the system.

### **Integrated Vibration and Pressure Analysis**



**Figure 8.** Pressure Suction

Source: Pressure measurement at pump suction side, PT Indah Kiat Pulp & Paper Tbk., Karawang Unit, 2026

To improve diagnostic accuracy, vibration analysis results are correlated with suction pressure data. As shown in Figure 8, the suction pressure is negative, indicating a significant pressure drop that may approach or fall below the fluid's vapor pressure, creating conditions conducive to cavitation.

From a hydraulic perspective, this condition is related to the Net Positive Suction Head Available ( $NPSH_a$ ). A decrease in suction pressure reduces  $NPSH_a$ , and when it approaches or falls below the required NPSH ( $NPSH_r$ ), cavitation may occur. Thus, the observed negative suction pressure indicates a reduction in  $NPSH_a$ , which is indicative of potential cavitation.

When correlated with the FFT spectrum, which shows broadband vibration and a hump in the mid- to high-frequency range, the results suggest that the dominant vibration source is related to hydraulic phenomena. This observation is consistent with diagnostic guidelines from the Mobius Institute, which characterize cavitation by non-discrete spectral patterns and elevated broadband energy rather than distinct harmonic peaks.

Therefore, the combination of negative suction pressure, reduced  $NPSH_a$ , and broadband vibration characteristics indicates that the pump is likely experiencing cavitation. This integrated approach demonstrates that combining vibration and pressure analysis provides a more reliable method for identifying the root cause of abnormal vibration in centrifugal pump systems.

## CONCLUSION

The integration of FFT-based vibration spectrum analysis with suction pressure parameters enables accurate differentiation between mechanical faults and cavitation in centrifugal pumps. Vibration analysis identifies mechanical faults such as unbalance and misalignment through distinct harmonic peaks at the rotational frequency and its multiples, while cavitation is characterized by broadband high-frequency vibration accompanied by a spectral hump. Suction pressure measurements provide additional confirmation of hydraulic conditions; a significant pressure drop indicates the likelihood of cavitation. The combined evaluation of vibration spectral features and suction pressure behaviour improves diagnostic reliability by distinguishing mechanically induced vibration from hydraulically induced vibration. This integrated approach has been proven effective for condition monitoring of centrifugal pumps and can be applied in predictive maintenance systems to enhance early fault detection and operational reliability under real industrial conditions. Based on these findings, it is recommended that industry practitioners, particularly the maintenance team at PT Indah Kiat Pulp & Paper Tbk., routinely integrate suction pressure measurements with FFT-based vibration spectrum analysis in their centrifugal pump condition monitoring programs, and conduct further investigation of the suction system to address the detected negative pressure in order to prevent more severe cavitation. For future researchers, it is recommended to develop artificial intelligence (AI) or machine learning-based diagnostic methods that integrate vibration and pressure data in real-time to improve prediction accuracy and fault classification, as well as to validate the proposed approach across various pump types and different operating conditions to enhance the generalizability of the research findings.

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