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Condition-Based Maintenance Optimization of Centrifugal Pumps Using Vibration Analysis Approach

Ahmad Haruna Muhammad^{1*}, Samora Nuhu Sada¹

¹*Department of Mechanical Engineering, Petroleum Training Institute, Effurun, Delta State-Nigeria*

*Corresponding author, muhammad_ah@edu.ng

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Abstract

Industrial machinery reliability can be enhanced by understanding the underlying root causes of system failures and implementing a robust maintenance strategy. Failures and maintenance activities data are always available in industries; however, proper and effective failure causes analysis is still lagging. As such, the benefits of maintenance strategy could not be realized, which has contributed to high operational and maintenance costs in production and manufacturing firms. This research work focuses on the maintenance optimization of centrifugal pumps used in Nigerian refineries to transport heavy petroleum products. In this study, The Griswold pump (101-PM-2A) was used, and its operational data was obtained from Warri Refining and Petrochemical Company, Ekpan (WRPC). The maintenance optimization method used in this research was Finite Element Analysis (FEA). The finite element analysis result showed that the vibration values of 28.858Hz are potentially safe to the pump as this is the value of the least natural frequency of one of the components (impeller) of the pump system. It is highly recommended that the operation of the pump has to be halted should a vibration reading close to 29Hz be registered on the vibrometer. The findings: optimized frequency values of 28.83Hz, inlet vibration value of 45.2 Hz, outlet vibration value of 45.35 Hz and volute vibration value of 44.99 Hz of this study, would be useful to maintenance practitioners and researchers toward achieving reliable operations.

Keywords: Centrifugal pump, impeller, volute, vibration, optimization

I. INTRODUCTION

Maintenance cost is an integral part of the total operating costs of all production and manufacturing plants. Depending on the specific industry, maintenance costs can represent between 15% and 40% of the cost of goods or services produced. In Iron and Steel industry and other heavy industries, maintenance costs represent up to 40% of the total production costs. Perhaps more important is the fact that our effective management of maintenance dramatically impacts our ability to manufacture quality products that are competitive in the world market. The loss of production time and product quality that result from inadequate maintenance management has had a dramatic impact on our inability to compete countries that have

implemented more advanced manufacturing and maintenance management philosophies (Odukoya, 2021). The dominant reason for the ineffective maintenance management is the lack of factual data that qualify the actual need for repairs or maintenance of plant machinery and systems. However, the development of microprocessor and other computer-based instrumentation used to monitor the operating condition of plant equipment, machinery and systems have provided the means to manage maintenance operations. This positive development has enabled us to reduce or eliminate unnecessary repairs and prevent catastrophic machine failures. Moreover, regular *monitoring* of actual machine conditions and operating efficiency of process systems ensure maintenance optimization thereby minimizing the number and costs of unscheduled outages created by machine-train failures and improve the overall availability of operating plants (Philip, 2013). Recent work by Liu et al. (2023) used a combination of Detached Eddy Simulation (DES) and cavitation models to optimize the performance of centrifugal pumps and understand the unsteady cavitation flow fields in pumps. Their research explores how cavitation interacts with turbulence and how energy loss concentrates in key areas like the impeller and volute, leading to performance deterioration under cavitating conditions. Jiang, et al. (2023) discussed how wear-ring clearance affects the efficiency and head of centrifugal pumps, with a focus on flow structures and pressure variations. Efficiency decreases with larger clearances, leading to increased energy losses. Almasi, A. (2023) investigated the impact of decentralized systems and variable-speed drives on centrifugal pump pressure optimization. He highlighted the benefits of variable-speed drives in managing pressure zones and reducing power consumption in pump systems. Chen, Y., & Yan, Q. (2023) scrutinised the impact of labyrinth seals on wear-ring clearance in centrifugal pumps (Springer Link). They explored how different wear-ring structures, such as labyrinth seals, enhanced overall efficiency and reduced hydraulic losses. Popela, E. (2023) did an optimization of pumping system design and performance using stochastic modelling. He addressed the integration of optimization techniques for managing pressure and flow variability in high-demand settings. Shi, M. et al. (2023) analysed centrifugal pump energy performance under fluctuating flow rates. The authors proposed methods to minimize energy losses during variable flow conditions, with a focus on temperature rise management. Popescu, G. et al. (2023) used advanced computational methods for centrifugal pump optimization. This study covered advances in CFD modelling, highlighting strategies for improving pump efficiency and pressure management through virtual simulations. Nguyen, V.T., & Vo, N. M. (2023) carried out works on optimization strategies in centrifugal pump design using AI and CFD analysis. They examined AI-integrated CFD analysis for pump optimization, revealing enhanced designs that improve flow rate, temperature control, and pressure stability. Solangi, Z., and Malik, A. (2023) investigated the influence of fluid temperature on pump pressure and head performance. They discussed the effects of temperature on fluid viscosity and its role in pump efficiency and pressure management. Cao, L. et al. (2023) carried out Wear-ring structural optimization to reduce hydraulic losses in centrifugal pumps. This study reviewed the impact of wear-ring structure on hydraulic losses and proposes new designs to enhance efficiency. In recent studies, RCM has been integrated with risk-based methodologies (such as Reliability-Based Maintenance, RBM), forming hybrid models like Reliability and Risk-Centred Maintenance (RRCM). These models not only evaluate the likelihood of failure but also consider risk estimation and the consequences of failures, making them particularly useful in industries where safety and environmental concerns are paramount, such as Oil and Gas. The RRCM model supports decision-making by providing a more detailed maintenance plan that considers both reliability and risk, addressing some limitations of the traditional RCM approach such as the lack of comprehensive risk evaluation (Geisbush & Ariaratnam, 2023).

II. METHODS

The method employed in this research is the utilization and comparison of simulation results of Finite Element Analysis (FEA) with field readings recorded from a particular pump in operation in order to predict

failures and suggest maintenance routine for the pump while in operation.

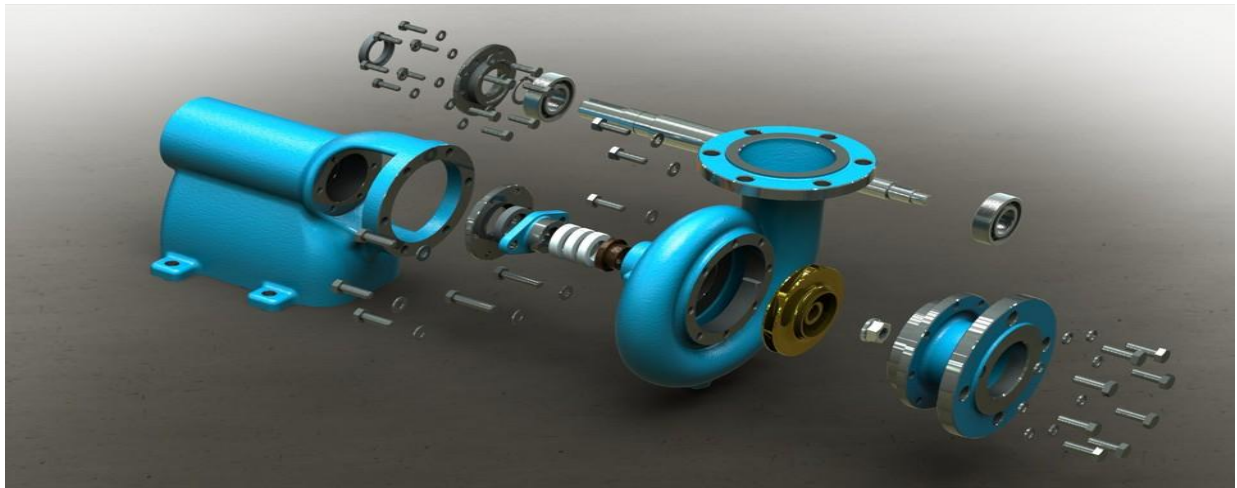


Figure 1: Centrifugal pump pictorial parts view (TQ Equipment, 2023)

The Griswold pump (101-PM-2A) was used as case a study and its operational data as well as field performance readings were obtained from WRPC. The tables below contain vibration data taken from Griswold (101-PM-2A) pump as follows:

Table 1: Sludge pump (Griswold) rating

liquid	Speed (RPM)	Power rating (Hp)	Voltage (Volts)	Frequency (Hz)	Discharge capacity (m ³ /h)	Head (m)	Temperature (Celsius)
Sludge	2950	50	380	40	25	150	32-50

Table 2: Material Properties of the Impeller

Material	Alloy Steel	
Elastic Modulus	210000	N/mm ²
Poisson's Ratio	0.28	N/A
Shear Modulus	79000	N/mm ²
Mass Density	7700	kg/m ³
Tensile Strength	723.8256	N/mm ²
Yield Strength	620.422	N/mm ²
Thermal Expansion Coefficient	1.30E-05	/K
Thermal Conductivity	50	W/(m·K)
Specific Heat	460	J/(kg·K)

Table 3: Field Recorded Vibration Data

Serial No	Date	Inlet vibration (Hz)	Outlet vibration (Hz)	Volute vibration (Hz)
1	27/3/2024	30.95	32.95	30.2
2	28/3/2024	28.61	34.6	38.15
3	30/3/2024	39.7	30.7	29.5
4	31/3/2024	34.8	30.15	33.95
5	03/3/2024	46.1	34.75	38.45
6	05/4/2024	33.6	34.4	26.35
7	7/4/2024	32.05	34.45	33
8	10/4/2024	30.4	34.75	34.4
9	12/4/2024	45.1	39.65	34.25
10	13/4/2024	39.05	35.15	34.3
11	14/4/2024	39.5	37.35	30.3
12	15/4/2024	29.35	32.15	33.8
13	17/4/2024	34.41	32.94	32.52
14	18/4/2024	29.3	28.15	29.45
15	20/4/2024	39.9	30.8	34.35
16	24/4/2024	30.7	32.2	30.65
17	26/4/2024	30.8	31.35	33.2
18	27/4/2024	34.6	33.2	32.3
19	1/5/2024	46.1	45.40	44.95
20	3/5/2024	37.7	31.25	32.95
21	5/5/2024	39.8	30.15	29.25
22	7/5/2024	30.6	31.25	28.3
23	15/5/2024	39.7	30.95	29.7
24	16/5/2024	31.45	34.9	32.1
25	19/5/2024	34.1	33.15	29.75
26	22/5/2024	34.7	34.2	33.9
27	24/5/2024	32.8	34.9	33.8
28	26/5/2024	34.6	32.5	33.9
29	29/5/2024	33.4	33.15	24.75
30	2/6/2024	34.35	33.5	45.15
31	5/6/2024	31.65	34.25	33.15
32	7/6/2024	30.95	31.45	39.85
33	9/6/2024	32.05	34.1	33.1

34	12/6/2024	30.35	23.6	32.65
35	14/6/2024	31.25	29.35	38.05
36	19/6/2024	31.85	30.05	31.45
37	21/6/2024	38.05	38.05	39.08
38	23/6/2024	33.75	33.25	32.6
39	26/6/2024	31.05	34.5	32.95
40	28/6/2024	45.2	45.35	44.99
41	30/6/2024	34.15	33.3	28.35
42	3/7/2024	38.8	39.25	31.5
43	5/7/2024	32.95	33.3	33.12
44	7/7/2022	30.2	33.75	32.95
45	10/7/2024	34.3	33.55	33.95

III. RESULTS

3.1 Mesh Sensitivity Analysis for the Finite Element Analysis (FEA)

The effect of various mesh sizes on the outcomes of the simulation was examined in order to establish the ideal mesh size for the FEA investigation. To assess any inconsistencies in the results, a preliminary investigation was carried out using four (4) different mesh sizes, and the corresponding result in terms of stress acting on the impeller in MPa was compared. Figure below shows the mesh result of different mesh sizes; 19.2mm, 9.6mm, 4.8mm and 2.4mm respectively.

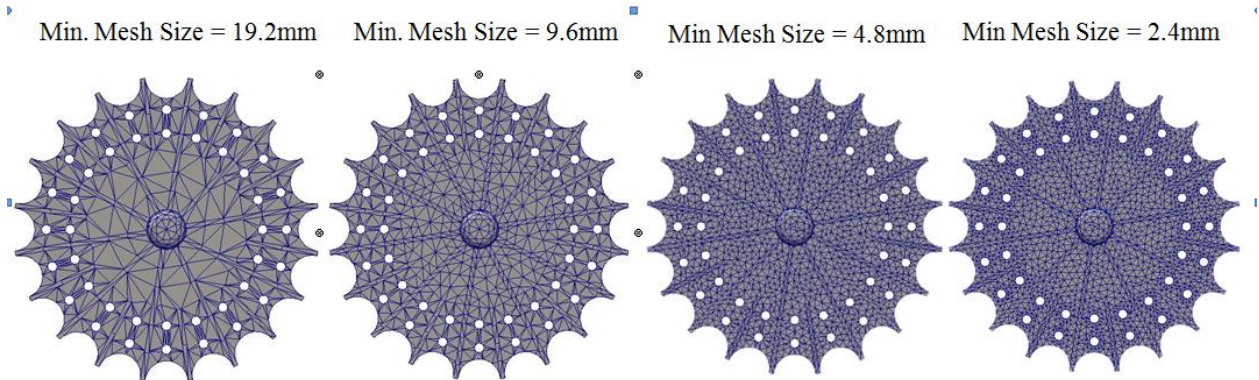


Figure 2: Different Mesh Sizes

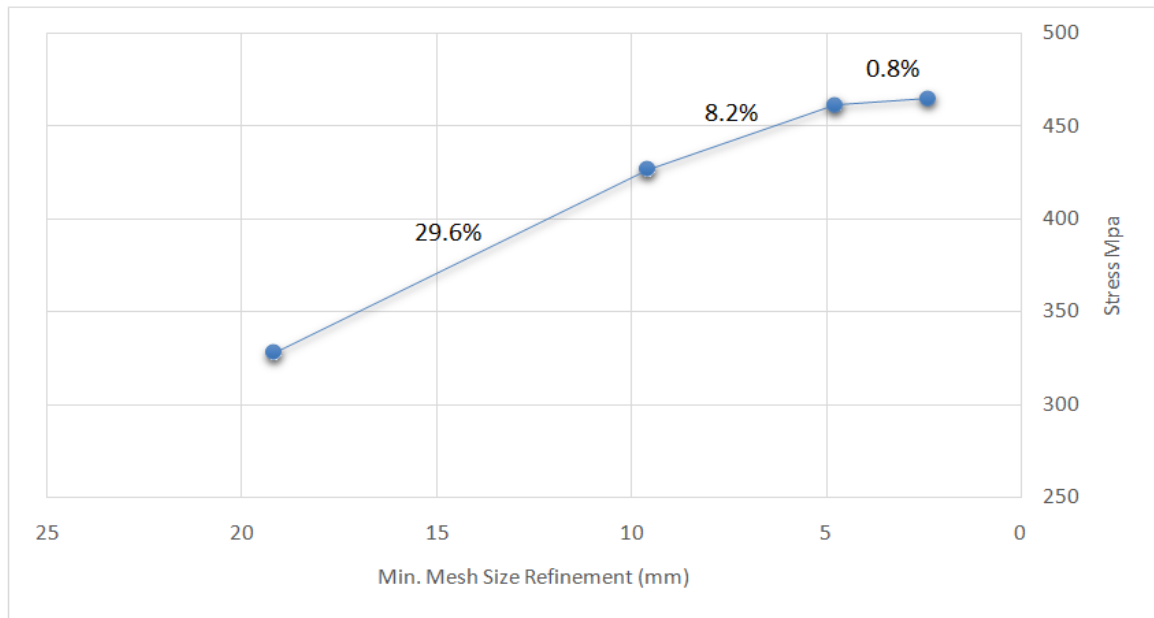


Figure 3: Graph showing the percentage discrepancy for different mesh sizes

Based on the analysis of discrepancies, it is evident that a minimum mesh size of 2.4mm is recommended for the FEA study of the impeller. The 0.8% discrepancy observed at this mesh size is negligible and ensures that the simulation results remain accurate while reducing computational effort.

3.2 Static Analysis of the Impeller

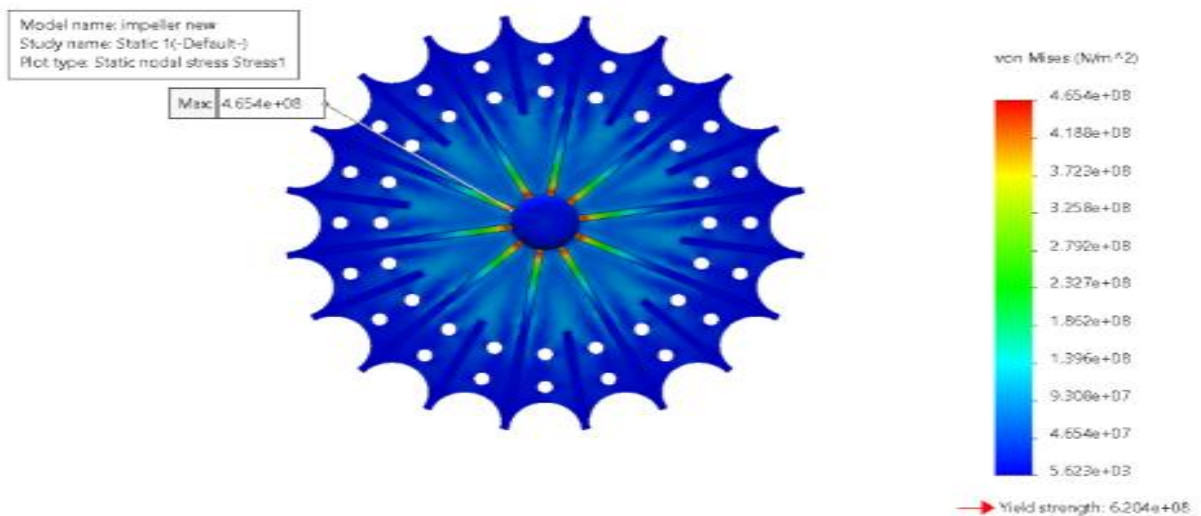


Figure 4: Von Mises Stress Distribution on the meshed impeller

From the figure 4, it can be seen that the impeller experiences the highest stress towards its eye and it fades out as it approaches its edges. The maximum stress observed ($4.654 \times 10^8 \text{ N/m}^2$) is below the yield strength of the impeller material, hence it is considered safe to operate with such pressure head.

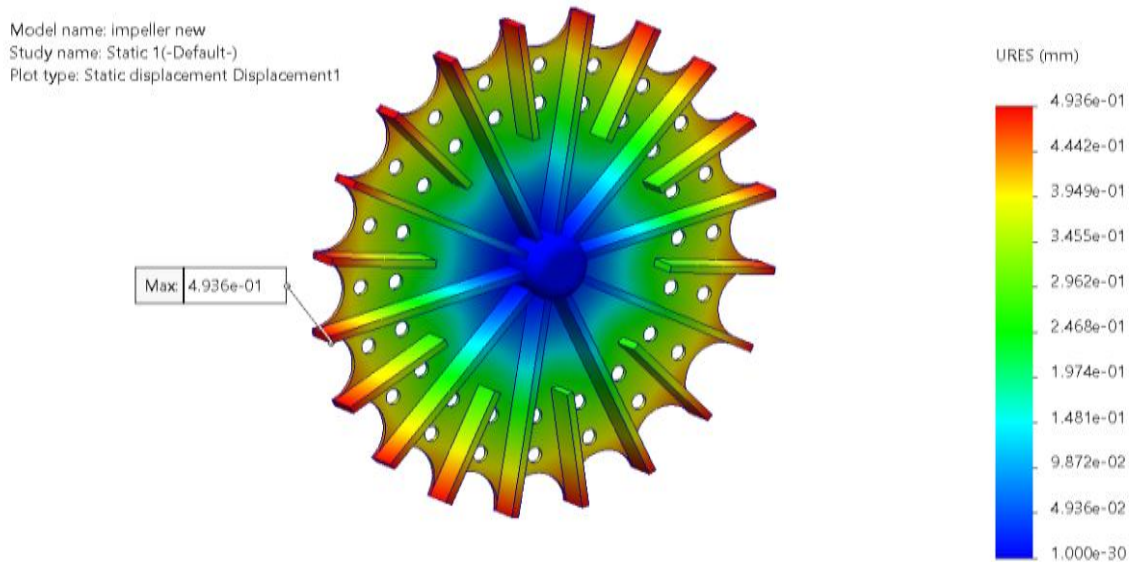


Figure 5: Maximum Deformation of the Impeller

3.3 Dynamic Analysis of the Impeller

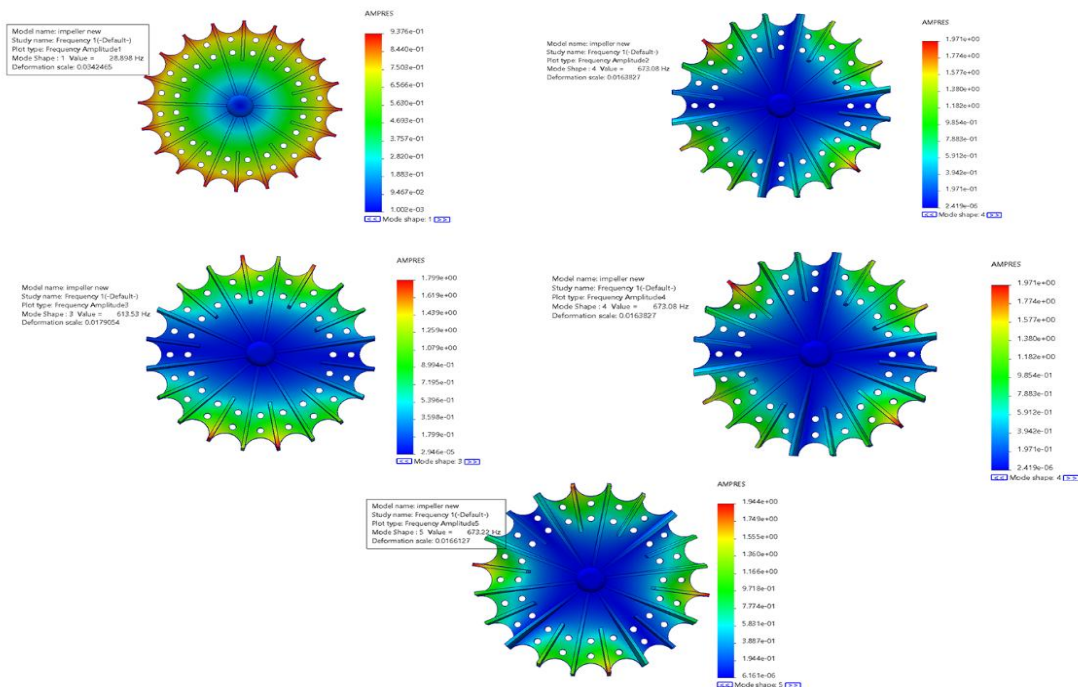


Figure 6: Modal Frequency Plots of Impeller

The maximum deformation on impeller due to same loading conditions is 0.4936mm (see fig. 5). This value is negligible hence it is not a threat to the usage of the impeller. The impeller eye experiences less deformation

than any other part, the deformation increases as it gets to the edges. From the simulation above (Fig. 6) the minimum and maximum natural frequencies obtained are 28Hz and 744Hz.

3.4 Static Analysis of the Volute

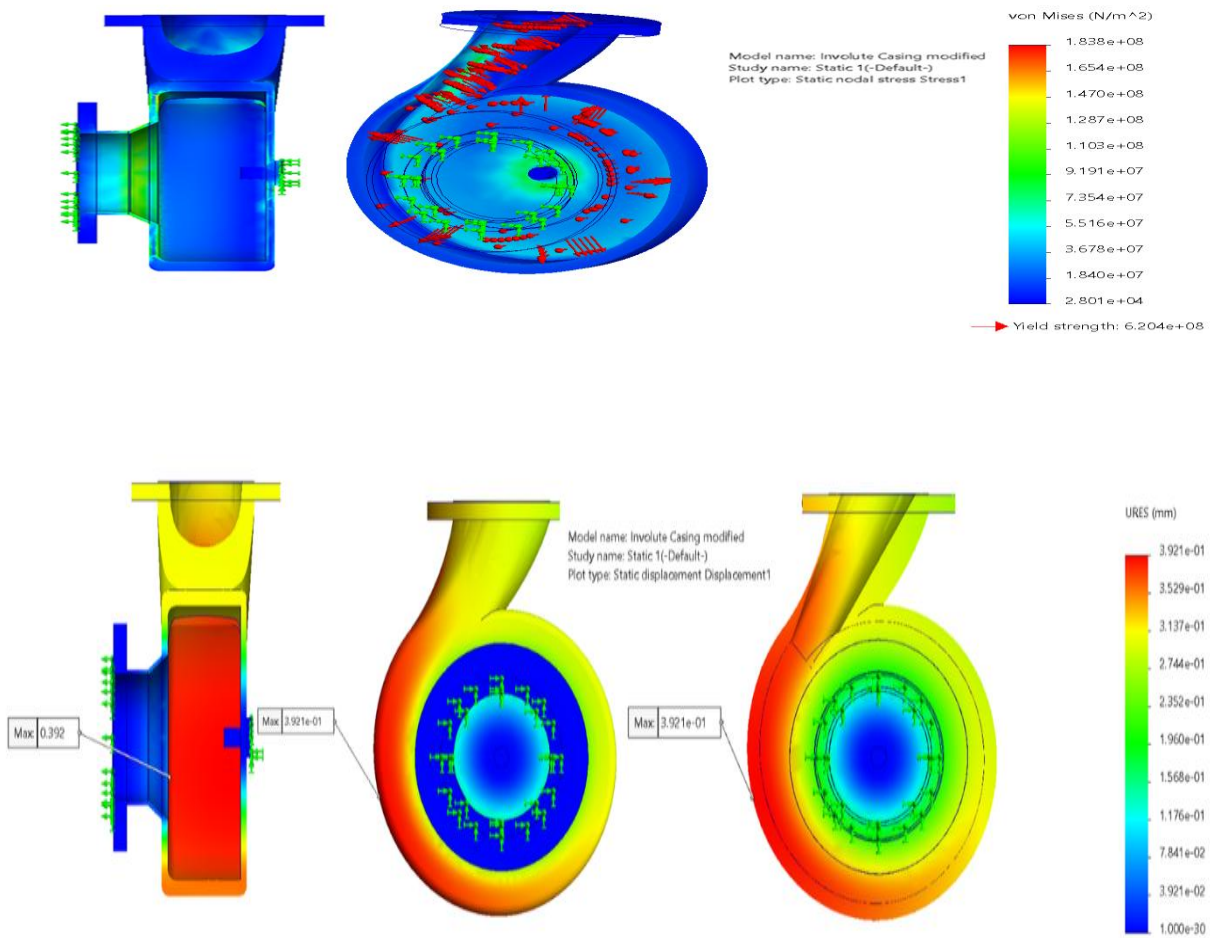


Figure 8: Volute Deformation Distributions

3.5 Dynamic Analysis of the Volute

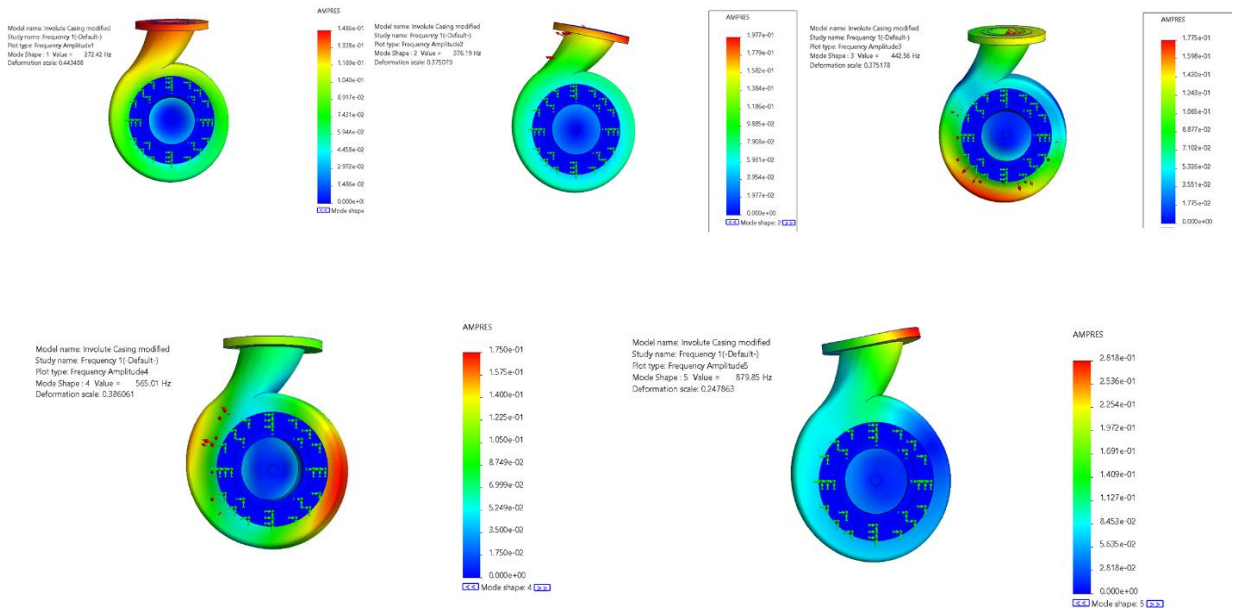


Figure 9: Modal Frequency Plots of Volute

From figure 7 above, it can be seen that the volute experiences the highest stress towards its edges. The maximum stress observed ($1.838 \times 10^8 \text{ N/m}^2$) is below the yield strength of the volute material, hence it is considered safe to operate with such pressure head.

Table 5: Result

Mode No.	Frequency (rad/sec)	Frequency (Hertz)	Period (Seconds)
1	181.57	28.898	0.034604
2	3,854.70	613.49	0.00163
3	3,854.90	613.53	0.0016299
4	4,229.10	673.08	0.0014857
5	4,230	673.22	0.0014854
6	4,418	703.15	0.0014222
7	4,480.60	713.12	0.0014023
8	4,482	713.33	0.0014019
9	4,669.20	743.13	0.0013457
10	4,675.40	744.11	0.0013439

The maximum deformation on the volute due to same loading conditions is 0.3921mm (see fig. 8). This value is negligible hence it is not a threat to the usage of the volute. From figure 4.6 above, the least natural frequency obtained from the simulation is 28.85Hz. Based on the result above (see table 5), the finite element analysis (FEA) model is very prompt to identifying early signs and symptoms of machinery failure which if

arrested would drastically reduce unplanned downtime, unnecessary part replacements, and catastrophic equipment failures and so on. The FEA simulation result suggested that the vibration values approaching 29Hz (which is the least natural frequency) are potentially catastrophic to the pump.

CONTRIBUTION TO KNOWLEDGE

This research establishes benchmarks for monitoring the operation of centrifugal pumps used in Oil and Gas and allied industries. The findings could significantly improve reliability, reduce maintenance costs and support sustainability goals across industries reliant on pump systems.

CONCLUSION

Operation of the pump should be halted should a vibration reading close to 29Hz be registered on the vibrometer. An immediate maintenance routine to rectify the effect of the excessive vibration should be carried out to avoid damage to the pump and downtime. Even while operating under safe conditions, due to the tendency of fatigue, the pump components should be examined after reasonable working cycles.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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