



DESIGN AND ANALYSIS OF CENTRIFUGAL PUMP IMPELLER

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Abstract

This research focuses on the modelling and analysis of a centrifugal pump impeller using Finite Element Method (FEM) in ANSYS Workbench. The impeller geometry was created using SolidWorks and then imported into ANSYS for further simulation. The aim of the study was to analyze the mechanical behaviour of the impeller under operational conditions by investigating total deformation and equivalent (Von-Mises) stress. Two materials—Stainless Steel and Aluminum Alloy, were selected for comparison based on mechanical strength and deformation response. The methodology included defining accurate material properties such as density, modulus of elasticity, tensile strength, and compressive strength within the Engineering Data module of ANSYS. A fine mesh was applied to the geometry to ensure result accuracy. Boundary conditions such as a rotational speed of 5 rad/sec and fixed support along the x-axis were set. The simulation was executed using the ANSYS solver, and output variables were selected for post-processing analysis. Results indicated that stainless steel exhibited minimal deformation (0.00009 mm) and slightly higher stress (28.503 MPa), whereas aluminum alloy showed greater deformation (0.002655 mm) with a slightly lower stress (27.412 MPa). A comparative study with previous literature confirmed that the selected materials operate within safe limits of stress and deformation. However, stainless steel outperformed aluminum in terms of rigidity and reduced deformation, suggesting its suitability for applications where mechanical durability is critical. This study highlights the effectiveness of FEM analysis in optimizing component design and material selection for rotating machinery like centrifugal pumps.

Keywords: Centrifugal pump impellers, FEM Analysis, Equivalent Stress, Total Deformation, and Design Optimization.

1. Introduction

Centrifugal pumps are fundamental in numerous industries, and their efficiency and reliability depend significantly on the design of their impellers. This comprehensive review paper delves into the intricacies of centrifugal pump

impeller design, offering a systematic and insightful overview of its principles, historical evolution, and contemporary innovations. Beginning with a foundation in the fundamentals of centrifugal pump operation, the review explores the historical roots of impeller design and its limitations. It then pivots to examine modern design strategies, underpinned by cutting-edge computational fluid dynamics (CFD), finite element analysis (FEA), and optimization techniques. A substantial portion of the review is dedicated to discussing recent advancements and emerging trends in impeller design. It scrutinizes the integration of advanced materials, geometric modifications, and computational methodologies, all aimed at achieving superior pump performance, efficiency, and reliability. Real-world case studies and practical applications underscore the tangible benefits of innovative impeller design. The review concludes by highlighting the profound impact of impeller design on the efficiency, sustainability, and competitiveness of various industries. It emphasizes the enduring need for ongoing research and development in this field, poised to drive transformative advancements in fluid handling technology. In summary, this comprehensive review serves as an invaluable resource for engineers, researchers, and practitioners engaged in centrifugal pump technology. It encapsulates the evolving landscape of impeller design, offering insights into both historical foundations and future horizons. Through a synthesis of knowledge, this review contributes to the continuous improvement of centrifugal pump performance and underscores their integral role in modern industrial processes.

1.1 Materials Used

a) **Aluminium Alloy**- Aluminium alloys, often abbreviated as Al alloys, are metallic compounds composed primarily of aluminium along with various alloying elements. These alloys exhibit a diverse range of properties, making them highly versatile in engineering applications. With a typical diameter ranging from a few micrometers to larger scales, aluminium alloys offer a compelling combination of attributes, including lightweight construction, excellent corrosion resistance, notable strength-to-weight ratio, and favorable thermal conductivity. Additionally, aluminium alloys are known for their malleability, ease of fabrication, and recyclability. Widely utilized in aerospace, automotive, construction, and consumer goods industries, these alloys play a pivotal role in modern manufacturing, providing essential solutions for a multitude of structural and functional requirements.

b) **Stainless Steel** -Stainless steel is a corrosion-resistant alloy primarily composed of iron, chromium, nickel, and other elements, with a wide range of applications. Its corrosion resistance is attributed to the formation of a protective chromium oxide layer on its surface. Stainless steel exhibits exceptional durability, high tensile strength, and resistance to extreme temperatures, making it suitable for diverse industries such as construction, healthcare, kitchenware, and transportation. The alloy's versatility, hygienic properties, and aesthetic appeal contribute to its widespread use in architectural structures, medical equipment, kitchen appliances, automotive components, and various other applications.

2. Literature Review

Araste, Z., et al. (2023) present study conducted by Araste, Sadighi, and Jamimoghaddam in 2023 offers a pioneering methodology for fault diagnosis in centrifugal pumps. Their approach utilizes electrical signature analysis in conjunction with Support Vector Machine (SVM) algorithms. By integrating these techniques, the researchers aimed to assess the effectiveness of this method in identifying faults within centrifugal pumps. This novel approach presents significant potential for advancements in predictive maintenance strategies and enhancing the reliability of pumps in industrial settings. The implications of this research are substantial for industrial applications involving centrifugal pumps. Abdulkhaev, Z., et al. (2023) focuses on exploring optimal control methods specifically tailored for centrifugal pumps.

The primary objective of their study is to enhance the efficiency and overall performance of these pumps. It is anticipated that the research delves into an array of control strategies aimed at optimizing pump operation, which may encompass various techniques such as speed control, utilization of variable frequency drives (VFDs), or possibly other advanced control mechanisms. The investigation likely involves assessing and comparing different control strategies to identify the most effective approaches for enhancing the performance of centrifugal pumps. Bois, G. (2023) delves into the complex dynamics associated with two-phase non-miscible liquid/gas flows specifically within radial centrifugal pumps. This investigation is anticipated to present a comprehensive review encompassing fundamental principles, challenges, and critical considerations relevant to the management of two-phase flows. This knowledge is particularly vital for industries such as oil and gas, chemical processing, and energy sectors where the handling of two-phase flows is integral to various operational processes. Part A of the study likely provides foundational insights into the intricate behaviors and characteristics exhibited by these complex flow patterns within the context of centrifugal pumps. It may focus on elucidating phenomena such as gas-liquid interactions, phase distribution, flow regimes, pressure fluctuations, and the impact of these factors on pump performance. Hundshagen, M., & Skoda, R. (2023) represents a significant contribution to the comprehension of two-phase non-miscible liquid/gas flows within radial centrifugal pumps, specifically through the utilization of Computational Fluid Dynamics (CFD) approaches. Their research, detailed in Part C of the study, emphasizes the development and application of improved models, which likely involves exploring advanced numerical simulations and sophisticated modeling techniques. The focus on advanced numerical simulations and modeling techniques indicates a commitment to refining the accuracy and reliability of predictions concerning flow behavior and performance within centrifugal pumps handling two-phase flows. Peng, W., et al. (2023).

The study conducted by Peng et al. in 2023 focuses on analyzing the inner flow characteristics within a specific type of centrifugal pump, namely the multi-stage double-suction centrifugal pump. To investigate the flow dynamics within this pump, the researchers employed the Detached Eddy Simulation (DES) method, a computational fluid dynamics (CFD) approach known for its capability to capture both resolved and modeled turbulent flow features. Wang, C. N., et al. (2022) centers on the utilization of Computational Fluid Dynamics (CFD) analysis coupled with

an effectively artificial intelligent algorithm. This research likely employs advanced methodologies, potentially involving machine learning or optimization-based approaches, to comprehensively analyze a centrifugal pump's performance and iteratively optimize its design parameters. Luo, X., et al. (2022) aims to delve into the analysis and research of vibration characteristics displayed by nuclear centrifugal pumps specifically under low flow rate conditions. This research likely involves a comprehensive investigation encompassing either experimental methodologies or numerical simulations to examine the vibration patterns exhibited by these pumps when operating at low flow rates. De Lazzari, et a. (2022) The research conducted by De Lazzari et al. in 2022 focuses on comprehensively analyzing the effects of right ventricular centrifugal pump assistance on cardiac performance. The study likely employs experimental or computational analyses to delve into the intricate dynamics of how assistance from a right ventricular centrifugal pump influences the cardiovascular system, specifically by examining pressure-volume relationships within the ventricles and atria.

Zhang, N., et al. (2020) In the study conducted by Zhang, N., et al. in 2020, researchers conducted a numerical analysis aimed at comprehensively examining the vortical structures and their unsteady evolution within a centrifugal pump. This research likely involved detailed computational simulations to investigate the formation, behavior, and dynamic evolution of vortical structures within the pump under various operational conditions. The primary focus of this study was likely to gain a deeper understanding of the complex flow phenomena occurring within the centrifugal pump, specifically concentrating on the formation and behavior of vortical structures. Al-Obaidi (2020) focuses on the detection of cavitation phenomena within a centrifugal pump, a common issue that can lead to performance deterioration and damage to pump components. The research likely utilizes vibration analysis techniques in both the time and frequency domains to detect and analyze cavitation effects occurring within the pump.

Cavitation in centrifugal pumps arises when localized low-pressure regions cause the formation and collapse of vapor bubbles within the flowing liquid. Zhang, N., et al. (2020) utilized Detached Eddy Simulation (DES) analysis to investigate the unsteady flow evolution and pressure pulsations occurring during an off-design condition of a centrifugal pump. This research likely employed advanced computational simulations to delve into how the pump's performance and flow characteristics evolve when operating under off-design conditions. Off-design conditions refer to operating scenarios where a pump functions outside its intended or optimal design parameters. Al-Obaidi, et al. (2019) revolves around an experimental investigation aimed at utilizing vibration signatures for detecting incipient cavitation in centrifugal pumps. The research likely involves employing envelope spectrum analysis techniques to identify subtle changes in vibration patterns indicative of the early stages of cavitation formation within the pump. Incipient cavitation refers to the initial phase or early onset of cavitation within the pump system.

3. Research Methodology

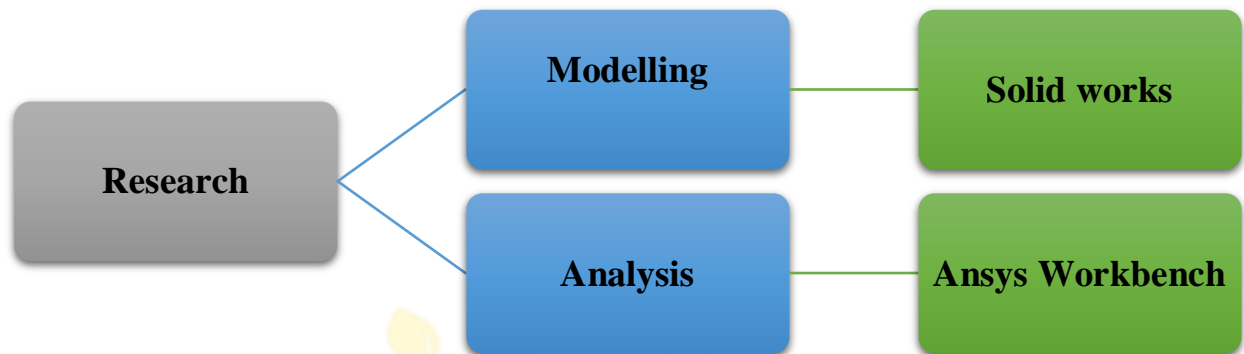


Figure 1. Research Methodology

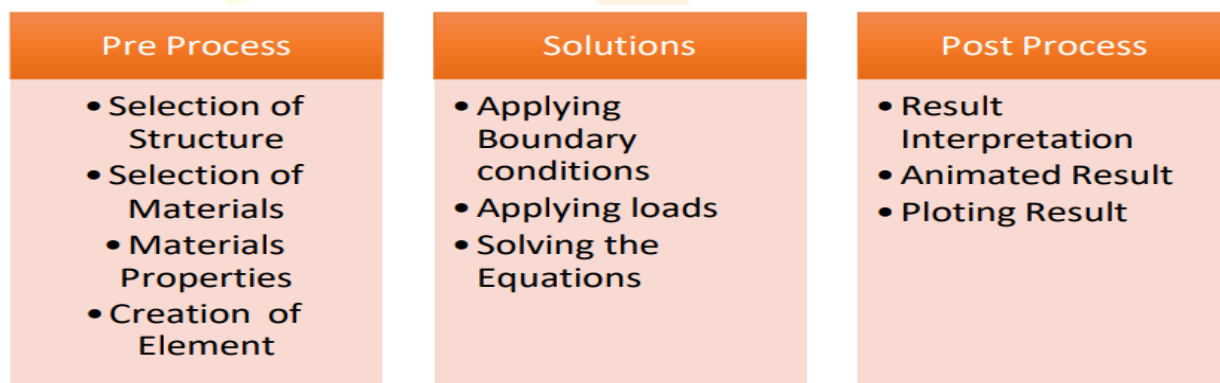
3.1 Methodological Approach for Modelling & Analysis

- a. Imported the geometry that built in Solid work into Design Workbench of ANSYS fluent analysis window.
- b. Defined material properties for centrifugal pump impeller model in the Engineering Data Such as, density, modulus of elasticity, tensile strength and compressive strength.
- c. The geometry was opened in the Ansys modeler window to perform rest of the activities such as meshing, boundary condition.
- d. Meshing of the blade was done and default meshing was selected for this meshing work here, the meshing size was fine.
- e. Boundary condition was applied such as Rotation (5 Rad/sec) and it was fixed about x-axis.
- f. After the boundary condition was applied the model was solved using Ansys solver.
- g. The next step was to select the output variables so here, the total deformation and Stress concentration was tested.
- h. The result was demonstrated using output display unit of Ansys workbench and the maximum and minimum value was shown. Shaft material is mainly low carbon/mild steel. Material we used are stainless steel and aluminum alloy, whose main properties are.

Table 1. Properties of materials selected for this design

Material name		Stainless steel
Density	kg/m ³	8
Yield strength	Mpa	205
% elongation	%	40
Poisons ratio	λ	0.27
Modulus of elasticity E	Gpa	193
Shear modulus	Gpa	86

Material name		Aluminum alloy
Density	kg/m ³	2700
Yield strength	Mpa	178
% elongation	%	40
Poisons ratio	λ	0.33
Modulus of elasticity E	Gpa	173
Shear modulus	Gpa	25

**Figure 2.** Steps used for FEM analysis

3.2 Modelling & Analysis

The geometry created in Solid work was imported into the Design Workbench of the ANSYS fluent analysis interface. Specified material parameters for the impeller model of a wind turbine in the Engineering Data. Density, modulus of elasticity, tensile strength, and compressive strength are examples. The geometry was loaded into the Ansys modeler window in order to conduct the remaining tasks, including meshing and boundary conditions. The meshing of the impeller was completed, and the default meshing size for this meshing job was fine.

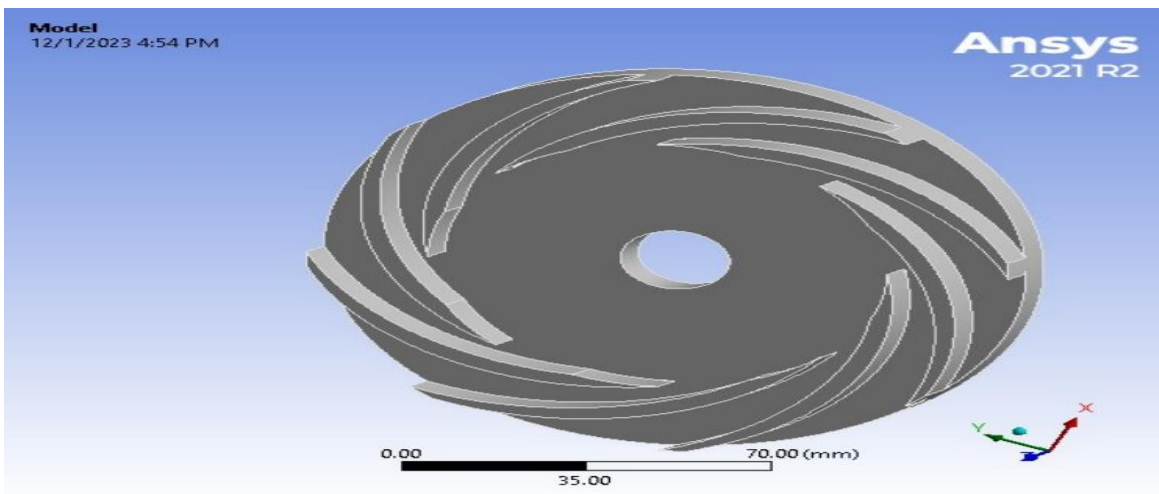


Figure 3. Model of Centrifugal Pump Impeller

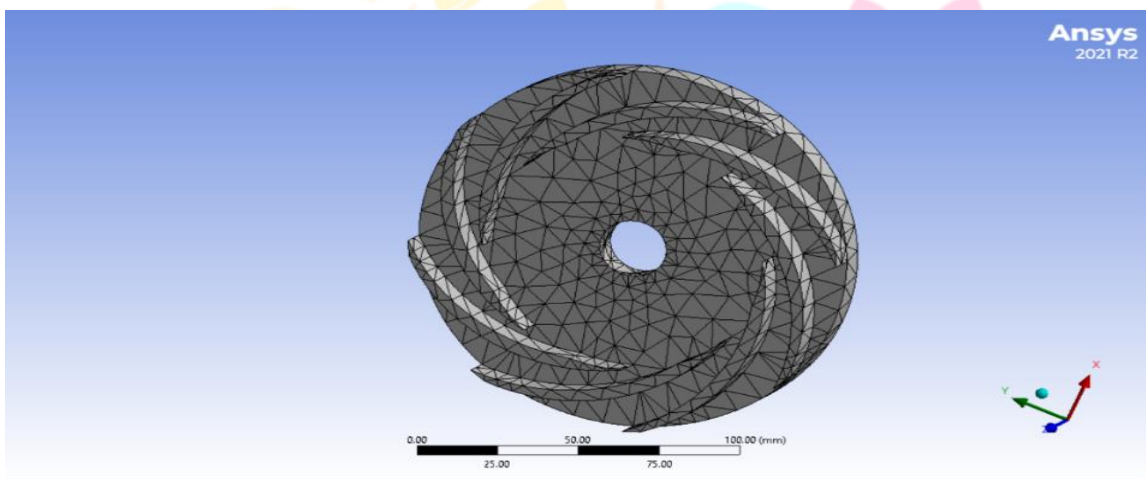


Figure 4. Meshing with fine size

After applying the boundary condition, the model was solved using the Ansys solver. Following the selection of the output variables, the total deformation, Stress concentration, and von-Mises stress were examined. Maximum and minimum values were displayed using the output display unit of Ansys workbench to showcase the outcome. The geometry that was constructed in Solid Work was imported into the Design Workbench of the ANSYS fluent analysis interface. Material properties for the impeller pump model have been defined in the Engineering Data. Such characteristics include density, the material's modulus of elasticity, as well as its tensile and compressive strengths.

4. Result and Discussion

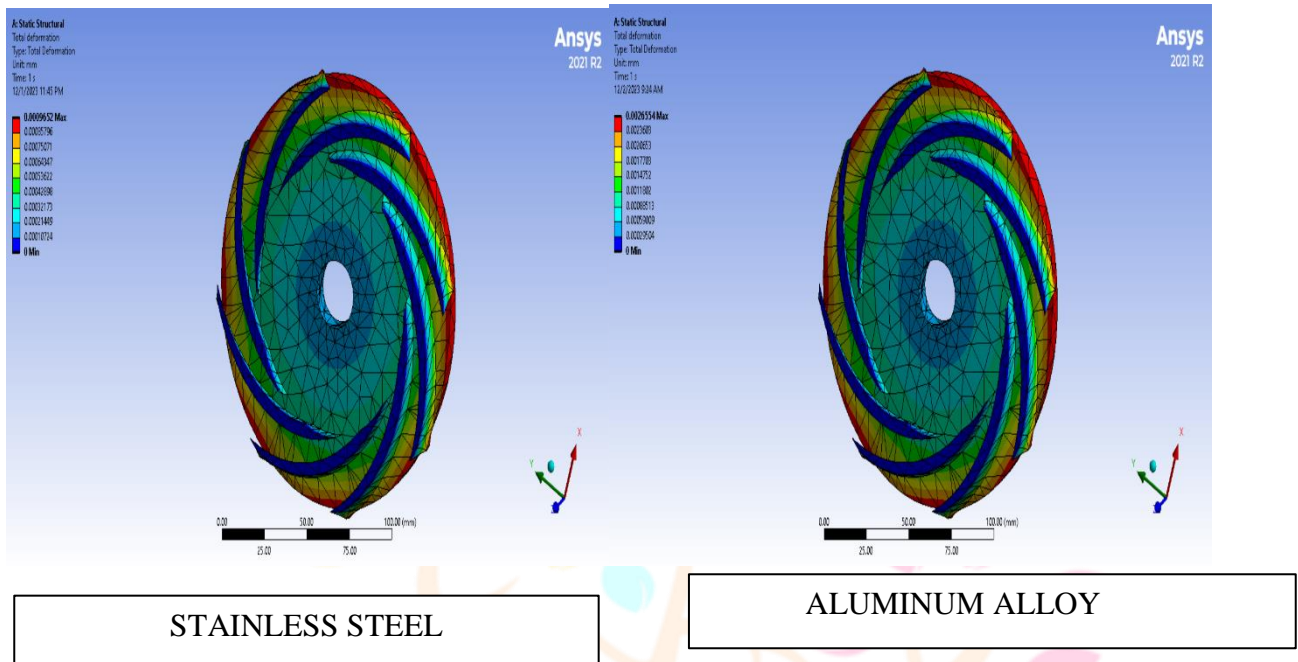


Figure 5. Total deformation

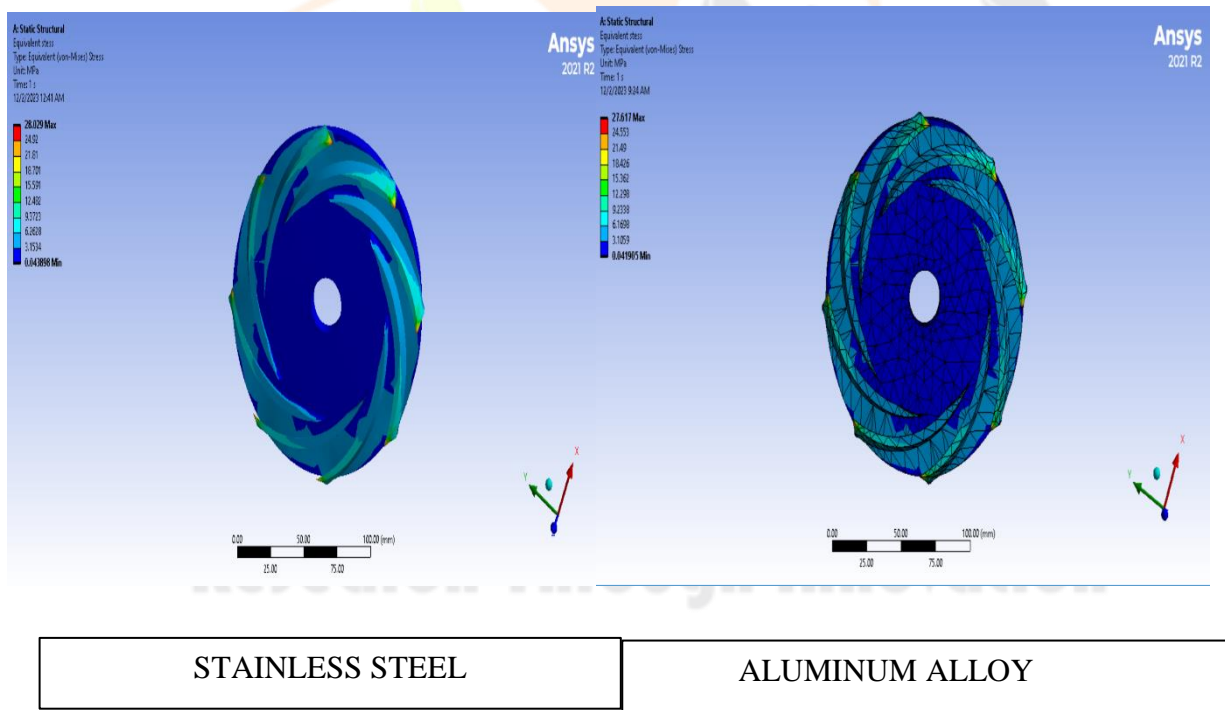


Figure 6. Equivalent stress

Two materials namely Stainless steel and Aluminum alloy were tested in this analysis. The maximum magnitude of Total deformation and Stress concentration were analyzed using Ansys workbench. Best out these two materials were analyzed for optimized design and for this minimum stress and deformation was tested.

Table 2. Comparison of model performance

Sr. No.	Material	Stress (MPa)	Deformation (mm)
1	Stainless Steel	28.503 MPa	0.00009
2	Aluminum Alloy	27.412 MPa	0.002655

As per the result that stainless steel has less deformation and stress induced in it is equal to then that of aluminium alloy so stainless steel is the great option for selection of material.

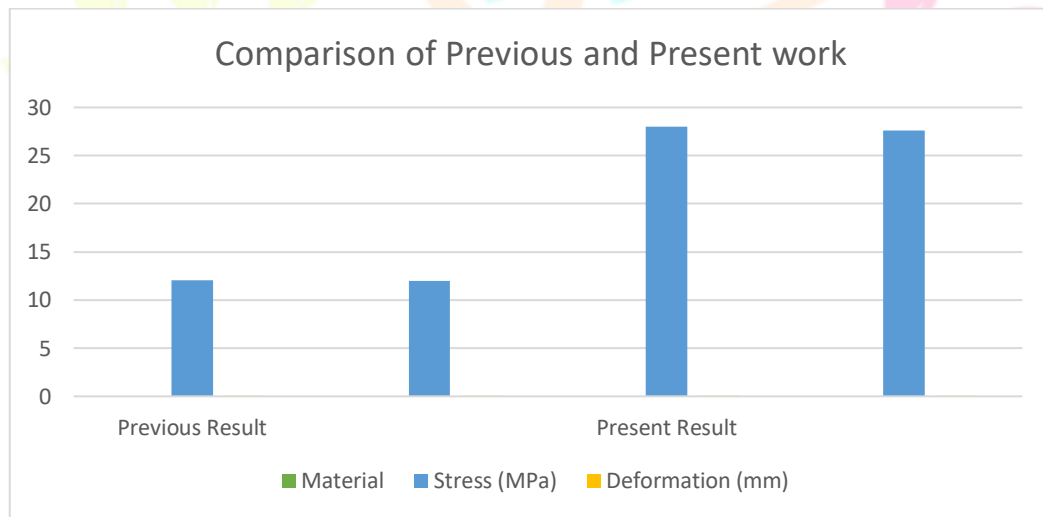


Figure 7. Comparison of Previous and Present work

Table 3. Previous Research Paper Reference Result Comparison

	Previous Result		Present Result	
	Mild Steel	Structural steel	Stainless steel	Aluminum Alloy
Stress (MPa)	12.043	11.974	28.027	27.61
Deformation (mm)	0.0028391	0.002961	0.0009652	0.0026554

The maximum deflection induced in metallic pump fan i.e. aluminum alloy material is 0.002655 mm, which is in safe limits. Hence based on rigidity the design is safe. The maximum induced stress for the same material is 27.613 MPa which is less than the allowable stress i.e working stress by considering factor of safety (160Gpa).Hence the design is safe based on strength. If we compare corresponding deformation of the material SS on above results aluminum alloy material, SS having minimum deformation therefore there are less chances of failure of the pump fan as compare to aluminum alloy materials. Hence the strength of pump gets increased because of the SS material.

5. Conclusion

The analysis carried out using FEM in ANSYS Workbench successfully demonstrated the structural behaviour of a centrifugal pump impeller under simulated operational conditions. The purpose of this study was to assess and compare the total deformation and stress distribution in impellers made of Stainless Steel and Aluminum Alloy, thereby identifying the more suitable material for practical application in pumping systems. From the simulation results, it was observed that Stainless Steel offered superior structural stability. It showed a significantly lower deformation of 0.00009 mm, indicating high rigidity and reduced vulnerability to mechanical failure. Although its stress level was slightly higher (28.503 MPa) compared to Aluminum Alloy (27.412 MPa), it remained well within the allowable stress limits, ensuring the design's safety under normal working conditions. On the other hand, Aluminum Alloy displayed more deformation (0.002655 mm), which could lead to performance issues over prolonged usage or under higher loading.

Furthermore, when the results were compared with earlier research, the performance of stainless steel was again found to be optimal due to its ability to resist both deformation and induced stress. The findings reinforce the importance of material selection in mechanical design and support the use of stainless steel in scenarios where strength and durability are essential. The FEM analysis method employed in this study proves to be an effective and accurate tool for virtual testing and optimization of mechanical components. It enables engineers to predict real-world performance without physically manufacturing multiple prototypes, thus saving cost, time, and resources. For centrifugal pump applications, especially those exposed to cyclic loads or high-stress environments, Stainless Steel is recommended as the preferred material for the impeller. Future work can incorporate thermal analysis, fluid-structure interaction, and fatigue analysis to further validate the design under comprehensive real-time operating conditions.

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