Performance Analysis of a Slotted Blade Impeller for Centrifugal Pump

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***Abstract*—This project focuses on the performance analysis of a slotted blade impeller for a centrifugal pump with the objective of improving hydraulic efficiency and flow stability. Conventional impellers often experience issues such as flow separation, recirculation, and non-uniform pressure distribution, which contribute to energy losses and reduced performance. To address these limitations, a modified impeller incorporating optimized blade slots is designed and analysed using 3D modelling and CFD simulation. The study evaluates key performance parameters including head, efficiency, velocity distribution, and turbulence characteristics for both conventional and slotted configurations. Results indicate that the slotted blade design enhances fluid guidance, reduces secondary flow effects, and delivers improved hydraulic output under the same operating conditions. The findings demonstrate the potential of blade-slot modifications as an effective and low-cost strategy for improving centrifugal pump performance and provide a foundation for further experimental validation and prototype development.**

***Index Terms*—B-pillar, composite materials, UTM.**

I. INTRODUCTION

Centrifugal pumps are among the most widely used fluid-handling machines across industrial, agricultural, and domestic sectors due to their simplicity, reliability, and ability to deliver stable flow under a wide range of operating conditions. Their performance, however, strongly depends on the geometric configuration and hydraulic characteristics of the impeller, which acts as the core energy-transfer component. Over the years, industries have placed increasing emphasis on enhancing pump efficiency, reducing energy consumption, and improving operational stability, as pumps account for a significant proportion of global industrial power usage. Despite the advancement of modern pump technologies, issues such as flow separation, recirculation, secondary flows, and vibration-induced instabilities continue to limit the performance of conventional impeller designs. These issues lead to reduced head, increased hydraulic losses, noise, structural fatigue, and premature failure, thereby creating a strong need for design improvements.

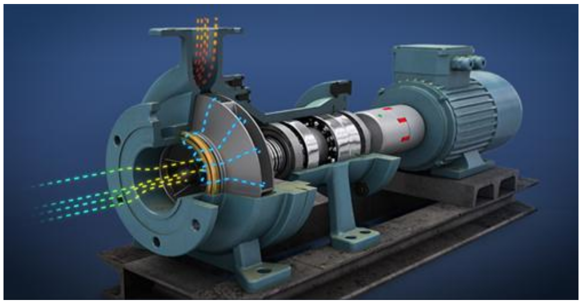


Fig No.1.1: Centrifugal Pump Assembly

In recent years, researchers have explored various impeller modifications to overcome these limitations, including changes in blade geometry, blade count, trailing edge profiles, and slot integration. Among these, slotted blade impellers have shown promising potential in improving internal flow behavior by offering alternative pathways for fluid redistribution inside the impeller. Introducing slots has been reported to reduce turbulence intensity, weaken vortical structures, and improve pressure uniformity across blade channels, contributing to enhanced hydraulic performance. Moreover, such modifications can often be implemented without major structural redesign, making them practical for industrial adoption.

Fig No.1.2: Slotted Blade Impeller

The growing demand for pumps capable of operating efficiently under varying load conditions further highlights the importance of design optimization. Industries such as water supply, petrochemicals, power generation, and wastewater management require pumps that maintain stable performance even under off-design conditions. The incorporation of slotted blade geometries offers a promising approach to meeting these requirements by improving flow regulation and mitigating instabilities that occur under fluctuating operating speeds. However, the structural implications of such geometric modifications especially their effect on modal frequencies and resonance behavior must be carefully evaluated to ensure reliable long-term performance.

This research focuses on the design, modeling, and analysis of a slotted blade impeller for a centrifugal pump using computational fluid dynamics (CFD) and finite element analysis (FEA). The study aims to investigate improvements in hydraulic efficiency, pressure distribution, and flow stability, while also evaluating the structural integrity through modal analysis. By comparing the slotted impeller to a conventional impeller, this work provides a deeper understanding of how slot geometry influences both fluid dynamics and vibrational characteristics. The findings contribute to the ongoing efforts in pump optimization, offering insights that can guide the development of more efficient, stable, and energy-conscious pumping systems

II. LITERATURE REVIEW

1. Wei Cui & Ziming Feng (2025)

Cui and Feng investigate slotted-blade impeller designs for electrical submersible pumps using a combination of parametric modeling, orthogonal design, and CFD analysis. Their study evaluates how slot parameters such as position, width, depth, and deflection angle influence internal flow behavior and pump performance. Results show that properly designed slots reduce flow separation, suppress recirculation near the trailing edge, and improve tangential velocity uniformity. The optimized slotted impeller demonstrates measurable gains in hydraulic efficiency and lower entropy production than a conventional design. The authors highlight manufacturability considerations and recommend experimental validation, especially under multiphase ESP conditions. Overall, the study provides a structured methodology for optimizing slotted blades and presents strong evidence of their performance benefits.

2. Muhammad Umair Najeem et al. (2024)

Najeem and colleagues review modern vibration-reduction strategies for centrifugal impellers, focusing on geometric tuning, material selection, and support-system improvements. They identify key excitation sources such as blade mistuning, imbalance, and blade–casing interactions. The paper emphasizes that small geometric adjustments and targeted stiffening can shift natural frequencies enough to avoid resonance without major redesign. Their review shows that modal tuning, dynamic balancing, and damping enhancement significantly reduce vibration amplitudes in practical pumps. They also note limitations of simulation-based solutions and the need for integrated fluid–structure interaction analysis. The authors conclude by highlighting gaps in long-term fatigue data and calling for standardized vibration-assessment methods.

3. Kiran C. More (2020)

More combines experiments and numerical simulations to study vibration characteristics in centrifugal blower impellers. The research shows that changes in blade thickness and rotational speed strongly influence natural frequencies and resonance behavior. Thicker blades increase structural stiffness and push modal frequencies higher, reducing resonance risk at common operating speeds. Experimental frequency-response measurements match well with FEM predictions, validating the numerical approach. The study also identifies aerodynamic forcing and imbalance as key contributors to vibrational excitation. More recommends optimized blade-thickness selection and future work involving FSI and noise analysis for better design refinement.

4. Hongliang Wang & Bing Long (2020)
Wang and Long analyze how slotted-blade parameters influence centrifugal pump performance using an L16 orthogonal test combined with CFD simulations. Their results show that slotting improves circumferential pressure uniformity, reduces trailing-edge separation, and mitigates secondary flows. Several slot configurations generate measurable increases in head and efficiency while reducing peak blade loading. The study highlights slot position as the most influential factor, with some placements producing beneficial mixing while others introduce additional losses. Practical considerations such as manufacturability and shifts in best-efficiency point are also discussed. Overall, the findings support slotting as a cost-effective method to enhance pump hydraulics.

5. Qidi Ke & Lingfeng Tang (2023)
Ke and Tang conduct an optimization study on slotted blades in low-specific-speed centrifugal pumps using response-surface methodology. Their analysis shows that slot geometry significantly impacts recirculation, wake strength, and energy losses, particularly near the blade trailing edge. The optimized slot parameters yield improvements in both head and efficiency, as well as a broader stable operating range. The response-surface model reveals strong interactions between slot depth, width, and position, emphasizing the need for multi-parameter optimization. The authors note manufacturability considerations and potential limitations in multiphase flow scenarios. Their work demonstrates how systematic optimization can produce practical, high-performing slotted-impeller designs.

6. Jong-Woong Yoon, Hyun Su Kang & Youn-Jea Kim (2022)
Yoon and co-authors evaluate slotted-impeller configurations for double-suction pumps to improve hydraulic symmetry and reduce secondary flows. Their CFD results show that well-placed slots reduce pressure imbalance between suction sides and suppress hub-region vortices. These modifications lead to smoother flow fields, lower cyclic loading, and slight improvements in head and efficiency. The study emphasizes the sensitivity of double-suction pumps to precise slot placement due to their dual-inlet structure. Practical benefits include reduced cavitation tendency and better axial-thrust balance. The authors recommend further transient and cavitation-inclusive studies for comprehensive validation.

7. Zheng et al. (2024)
Zheng and colleagues optimize impeller geometry and operating strategies for variable-speed centrifugal pumps designed for wide flow and head ranges. They test parametric changes in blade angle, wrap, diameter, and hub design, supported by CFD and experimental model validation. The optimized impeller maintains higher efficiency across varying speeds while improving cavitation margin and hydraulic stability. Their work also proposes a speed-scheduling method tailored to the pump’s optimized geometry for improved system-level energy performance. The results show that a single optimized impeller can reduce reliance on multi-pump staging in large installations. Limitations include system-specific geometry and inflow assumptions requiring recalibration for broader applications.

8. Li, H. (2023)
Li investigates how different trailing-edge geometries affect centrifugal pump performance, focusing on pressure recovery, wake patterns, and entropy-based energy losses. Simulations show that thinner and smoother trailing edges reduce wake strength and lower entropy production, improving overall hydraulic efficiency. Conversely, thicker trailing edges increase vortex shedding and may impact cavitation characteristics negatively. The study uses detailed loss analysis to explain the thermodynamic basis for performance differences. Li highlights trade-offs between hydraulic efficiency and structural robustness at the trailing edge. The paper concludes that trailing-edge refinement is a simple yet impactful design improvement for performance optimization.

9. Zhang, Y. (2023)
Zhang applies inverse-design techniques to develop impeller blade shapes based on target exit-flow distributions rather than conventional forward design. The approach yields geometries that produce more uniform outlet velocity fields, reduced secondary

flows, and improved efficiency. CFD validation confirms lower shear regions and decreased backflow in the inverse-designed impeller compared to the baseline. The study explains numerical challenges in inverse design and describes methods to maintain manufacturable geometry. Zhang emphasizes the potential of this method for tailoring impellers to specific application requirements. The work shows promise for rapid, high-performance impeller development with reduced design iteration cycles.

10. Kang et al. (2024)
Kang and colleagues analyze slurry transport in a pump equipped with dual inlets and a double-layered impeller using multiphase CFD methods. Their results show improved particle distribution, reduced recirculation, and lower erosion risks compared to conventional impeller designs. The dual-layer configuration helps prevent particle accumulation and enhances hydraulic stability under sand–water mixture flow. Key performance indicators such as pressure rise and predicted wear rates demonstrate the design's suitability for mining and dredging applications. The authors note limitations in long-duration wear predictions and encourage experimental testing. Their study underscores how geometric innovation can significantly improve slurry-handling performance.
lty of work: The novelty of this project lies in its focused investigation of a slotted blade impeller design specifically applied to a standard centrifugal pump, with a dual emphasis on hydraulic performance enhancement and vibration/resonance behavior a combination rarely explored together in previous studies. Unlike existing research that primarily concentrates on either flow improvement or structural dynamics in isolation, this work integrates CFD-based hydraulic analysis with modal analysis to understand how slot geometry influences both efficiency and dynamic stability. A major innovative aspect is the comparative evaluation between conventional impellers and newly designed slotted impellers, highlighting how simple geometric modifications can reduce secondary flows, improve pressure uniformity, and influence natural frequencies. The study uniquely identifies that while slotting offers hydraulic benefits, it also lowers natural frequencies, making resonance a more critical design factor an insight crucial for real-world pump reliability. Furthermore, the project provides an optimized slotted-blade configuration developed through a systematic design and analysis approach, contributing a new design reference for future energy-efficient and vibration-stable centrifugal pump development.

III. PROBLEM STATEMENT

- Conventional centrifugal pump impellers often suffer from flow separation, turbulence, and energy losses, which reduce hydraulic efficiency and create unstable operating conditions.
- Although geometric modifications such as blade slotting show potential for improving flow behavior, their combined impact on pump performance and structural dynamics remains insufficiently understood.
- There is a lack of comprehensive studies that simultaneously assess hydraulic enhancements and resonance risks associated with slotted blade designs.
- Therefore, a detailed investigation is required to determine whether a slotted blade impeller can deliver improved efficiency while maintaining acceptable vibrational stability compared to a standard impeller.

IV. OBJECTIVE

The aim of this project is to design and analyze a slotted blade impeller for a centrifugal pump to determine its effectiveness in improving hydraulic performance, enhancing flow stability, and increasing overall pump efficiency compared to a conventional impeller. The primary objectives are.

The primary objectives are as follows:
- Design and 3D modelling of slotted-blade impeller using CAD software.
- Perform FEA-based modal analysis to determine the natural frequencies and corresponding mode shapes of the slotted blade impeller, identifying potential resonance risks within the pump's operating range.
- To conduct experimental modal analysis using FFT analyzer and impact hammer test.

V. RESEARCH METHODOLOGY

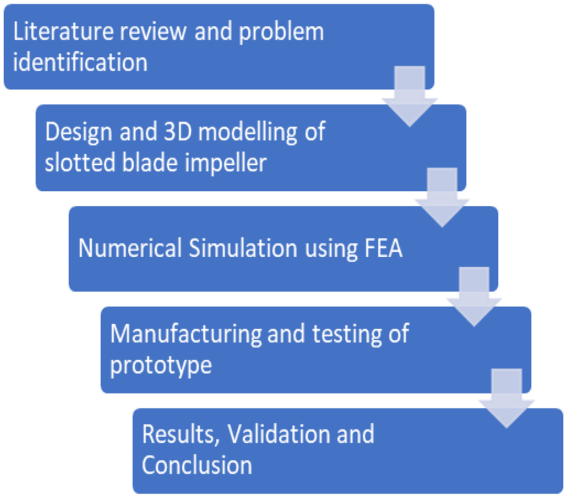


Fig No.5.1: Research Methodology

VI. FINITE ELEMENT ANALYSIS

The finite element method (FEM), is a numerical method for solving problems of engineering and mathematical physics. Typical problem areas of interest include structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential. The analytical solution of these problems generally require the solution to boundary value problems for partial differential equations. The finite element method formulation of the problem results in a system of algebraic equations. The method yields approximate values of the unknowns at discrete number of points over the domain. To solve the problem, it subdivides a large problem into smaller, simpler parts that are called finite elements.

In the first step, the element equations are simple equations that locally approximate the original complex equations to be studied, where the original equations are often partial differential equations (PDE). The process, in mathematical language, is to construct an integral of the inner product of the residual and the weight functions and set the integral to zero. In simple terms, it is a procedure that minimizes the error of approximation by fitting trial functions into the PDE. The residual is the error caused by the trial functions, and the weight functions are polynomial approximation functions that project the residual. The process eliminates all the spatial derivatives from the PDE, thus approximating the PDE locally with:

- A set of algebraic equations for steady state problems,
- A set of ordinary differential equations for transient problems.

These equation sets are the element equations. They are linear if the underlying PDE is linear, and vice versa. Algebraic equation sets that arise in the steady state problems are solved using numerical linear algebra methods, while ordinary differential equation sets that arise in the transient problems are solved by numerical integration using standard techniques such as Euler's method or the Runge-Kutta method.

FEM is best understood from its practical application, known as finite element analysis (FEA). FEA as applied in engineering is a computational tool for performing engineering analysis. It includes the use of mesh generation techniques for dividing a complex problem into small elements, as well as the use of software program coded with FEM algorithm. In applying FEA, the complex problem is usually a physical system with the underlying physics such as the Euler-Bernoulli beam equation, the heat equation, or the Navier-Stokes equations expressed in either PDE or integral equations, while the divided small elements of the complex problem represent different areas in the physical system.

In present research for analysis ANSYS (Analysis System) software is used. Basically, its present FEM method to solve any problem. Following are steps in detail.

1. Geometry
2. Discretization (Meshing)
3. Boundary condition
4. Solve (Solution)
5. Interpretation of results

Workbench contain analysis of different types namely static, modal, harmonic, explicit dynamics, CFD, ACP tool post, CFX, topology optimization etc. as per problem defined.

Step 1: Details of material namely copper, steel, grey cast iron, composite material, fluid domain material is defined in engineering data. i.e. ANSYS default material is structural steel.

Step 2: Import of geometry created in any CAD software namely CATIA, PRO E, SOLIDWORK, INVENTOR etc. in geometry section. If any correction is to be made it can be created in geometry section in Design modeller or space claim.

Step 3: In model section after import of component

- Material is assigned to component as per existing material
- Connection is checked in contact region i.e. bonded, frictionless, frictional, no separation etc. for multi body components.
- Meshing or discretization is performed i.e. to break components in small pieces (elements) as per size i.e. preferably tetra mesh and hexahedral mesh for 3D geometry and for 2 D quad or tria are generally preferred.

Step 4: Boundary condition is applied as per analysis namely in fixed support, pressure, force, displacement, velocity as per condition.

Step 5: Now problem is well defined and solve option is selected to obtain the solution in the form of equivalent stress, strain, energy, reaction force etc.

Modal Analysis:

Modal analysis is a fundamental technique used to determine the dynamic characteristics of a structure, including its natural frequencies, mode shapes, and damping factors. It provides insight into how a system behaves under vibratory loads and helps identify critical frequencies where resonance may occur. In engineering applications such as crankshaft design, understanding these modal parameters is essential to ensure structural integrity, minimize vibration, and enhance fatigue life.

The process of modal analysis involves extracting modal parameters from measured or simulated vibration data. Depending on how the data is acquired, modal analysis can be performed in the frequency domain or the time domain. When frequency response function (FRF) data is available, the analysis involves curve fitting these FRF curves using a predefined mathematical model that represents the dynamic behavior of the structure. This model accounts for the system's degrees of freedom (DoFs), damping characteristics, and the expected number of vibration modes within the frequency range of interest.

Accurate curve fitting is crucial because it directly determines the precision of the derived modal parameters. The quality of modal analysis depends not only on the mathematical fitting procedure but also on the accuracy of the measured data and the validity of the assumed structural model. If the chosen mathematical representation does not reflect the actual physical behavior of the structure, even a numerically minimized error function may yield unreliable results. Every mechanical system possesses certain resonant frequencies, also referred to as natural frequencies, at which it tends to vibrate when excited. These are the frequencies where the structure exhibits maximum amplitude response due to the efficient transfer of energy. As excitation frequency approaches a resonant frequency, the amplitude of vibration significantly increases, leading to potential structural failure if not properly controlled. Therefore, identifying and avoiding these resonance points is critical in design optimization.

6.1 Modal Analysis of Existing Impeller

1. Geometry:

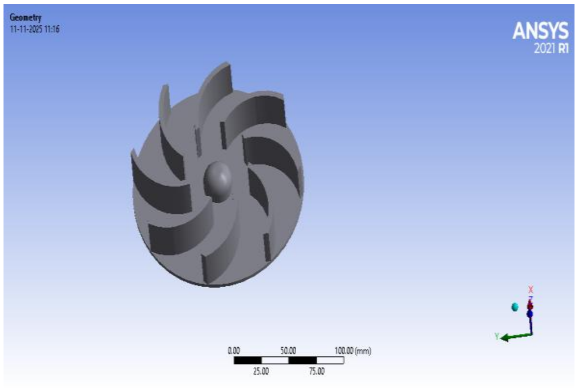
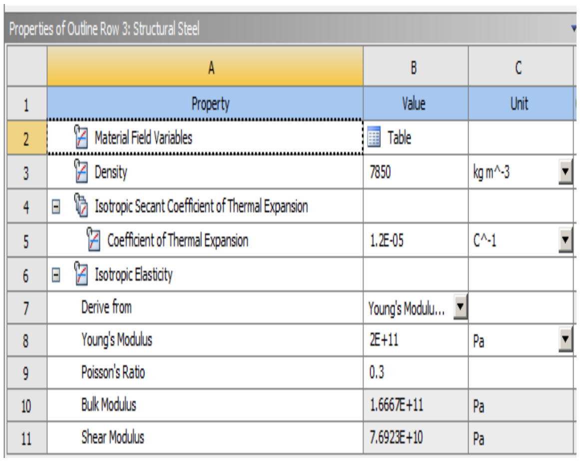


Fig No.6.1: Geometry of existing impeller.

2. Material Properties:

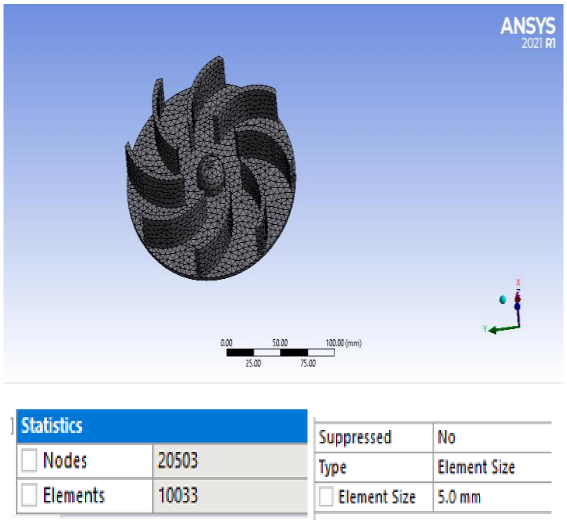


Properties of Outline Row 3: Structural Steel

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	7850	kg m^-3
4	⊟ Isotropic Secant Coefficient of Thermal Expansion		
5	Coefficient of Thermal Expansion	1.2E-05	C^-1
6	⊟ Isotropic Elasticity		
7	Derive from	Young's Modulu...	
8	Young's Modulus	2E+11	Pa
9	Poisson's Ratio	0.3	
10	Bulk Modulus	1.6667E+11	Pa
11	Shear Modulus	7.6923E+10	Pa

Fig No.6.2: Material properties of structural steel.

3. Meshing:



Statistics	
☐ Nodes	20503
☐ Elements	10033

Suppressed	No
Type	Element Size
☐ Element Size	5.0 mm

Fig No.6.3: Meshing Details of existing impeller.

4. Boundary Conditions:

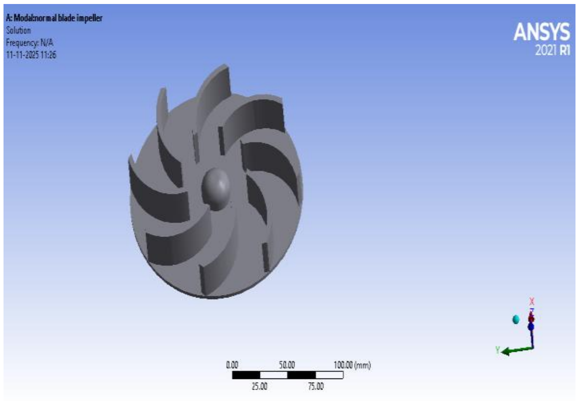


Fig No.6.4: Boundary conditions for modal analysis of existing impeller.

5. Results:

a) Mode Shape 1:

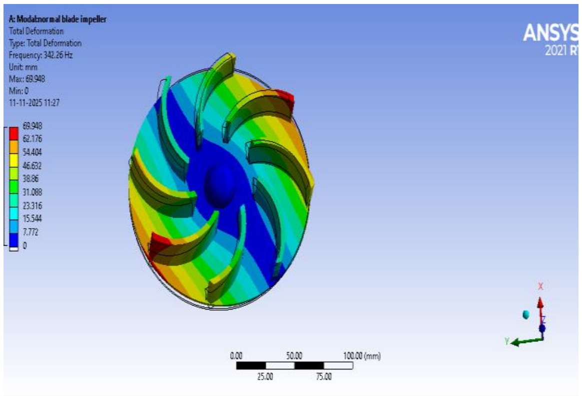


Fig No.6.5: Total Deformation for Mode Shape 1 for existing impeller.

b) Mode Shape 2:

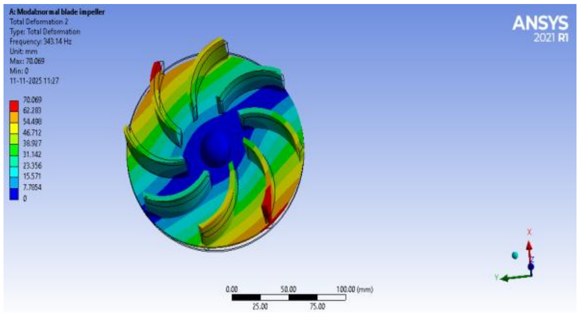


Fig No.6.6 Total Deformation for Mode Shape 2 for existing impeller.

c) Mode Shape 3:

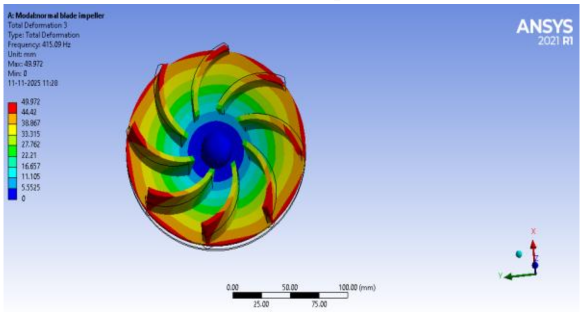


Fig No.6.7: Total Deformation for Mode Shape 3 for existing impeller.

d) Mode Shape 4:

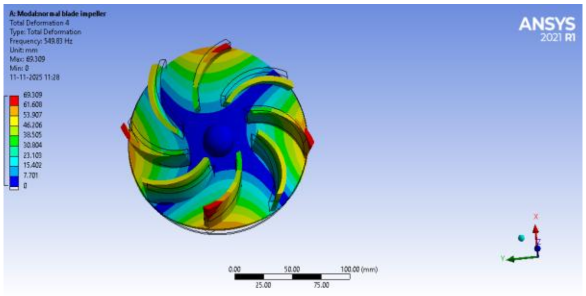


Fig No.6.8: Total Deformation for Mode Shape 4 for existing impeller.

e) Mode Shape 5:

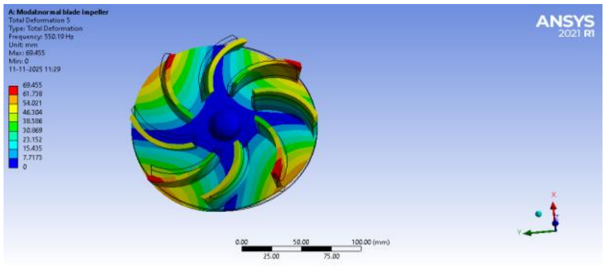


Fig No.6.9: Total Deformation for Mode Shape 5 for existing impeller

f) Mode Shape 6:

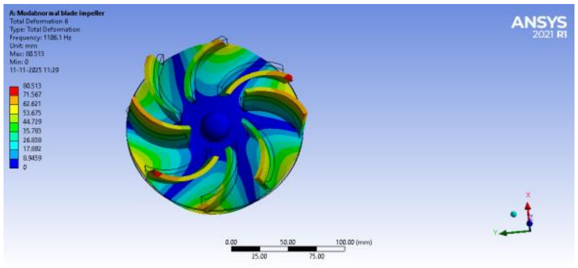
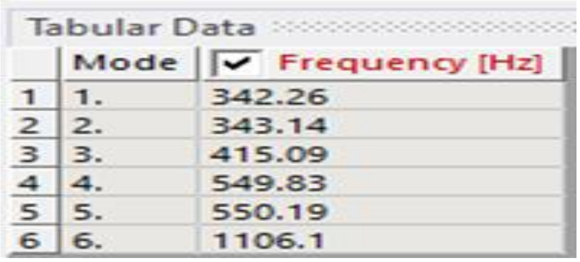


Fig No.6.10: Total Deformation for Mode Shape 6 for existing impeller



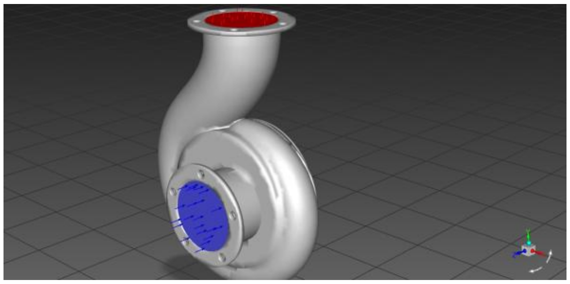
Tabular Data

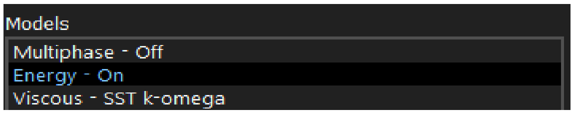
	Mode	✓ Frequency [Hz]
1	1.	342.26
2	2.	343.14
3	3.	415.09
4	4.	549.83
5	5.	550.19
6	6.	1106.1

Table. 6.1: Mode no. and their frequencies for existing impeller

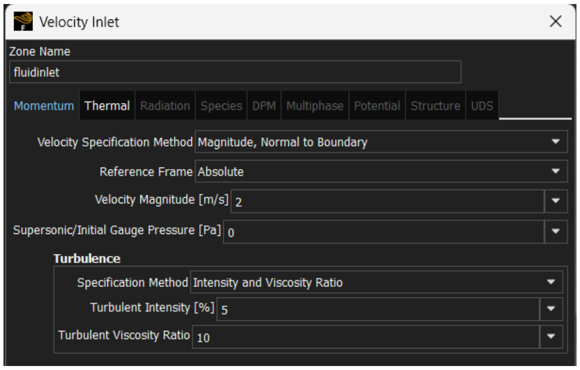
6.2 Fluent Analysis of Centrifugal Pump with Existing Impeller

1. Boundary Conditions:





Models
Multiphase - Off
Energy - On
Viscous - SST k-omega

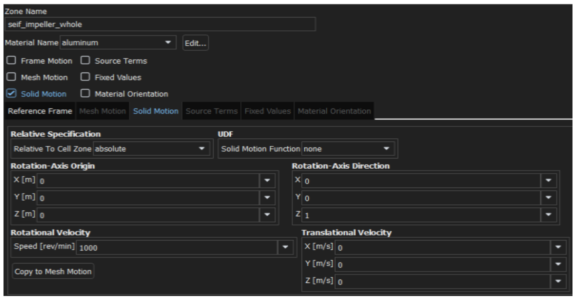


Velocity Inlet

Zone Name: fluidinlet

Velocity Specification Method: Magnitude, Normal to Boundary
Reference Frame: Absolute
Velocity Magnitude [m/s]: 2
Supersonic/Initial Gauge Pressure [Pa]: 0

Turbulence
Specification Method: Intensity and Viscosity Ratio
Turbulent Intensity [%]: 5
Turbulent Viscosity Ratio: 10



Zone Name: seif_impeller_whole
Material Name: aluminum

☐ Frame Motion ☐ Source Terms
☐ Mesh Motion ☐ Fixed Values
☑ Solid Motion ☐ Material Orientation

Relative Specification
Relative To Cell Zone: absolute

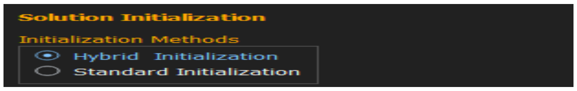
UDF
Solid Motion Function: none

Rotation-Axis Origin
X [m]: 0
Y [m]: 0
Z [m]: 0

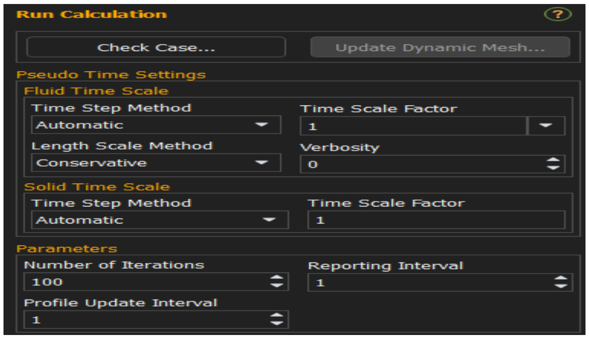
Rotation-Axis Direction
X: 0
Y: 0
Z: 1

Rotational Velocity
Speed [rev/min]: 1000

Translational Velocity
X [m/s]: 0
Y [m/s]: 0
Z [m/s]: 0



Solution Initialization
Initialization Methods
● Hybrid Initialization
○ Standard Initialization



Run Calculation

Pseudo Time Settings

Fluid Time Scale
Time Step Method: Automatic
Time Scale Factor: 1
Length Scale Method: Conservative
Verbosity: 0

Solid Time Scale
Time Step Method: Automatic
Time Scale Factor: 1

Parameters
Number of Iterations: 100
Reporting Interval: 1
Profile Update Interval: 1

Fig. No. 6.11: Boundary conditions for fluent analysis of centrifugal pump with existing impeller.

2. Results:

a) Pressure Contour:

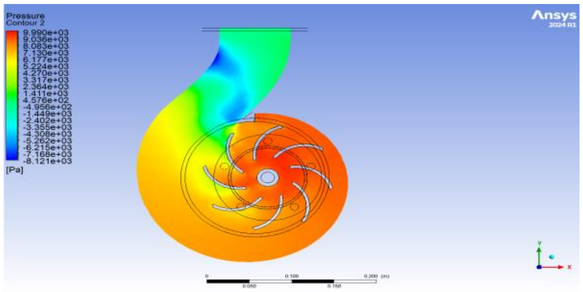


Fig. No. 6.12: Pressure contour of Centrifugal pump with existing impeller.

b) Velocity Contour:

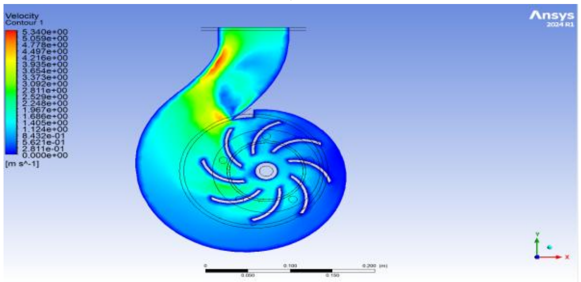


Fig. No. 6.13: Velocity contour of Centrifugal Pump with existing impeller.

c) Velocity Streamline:

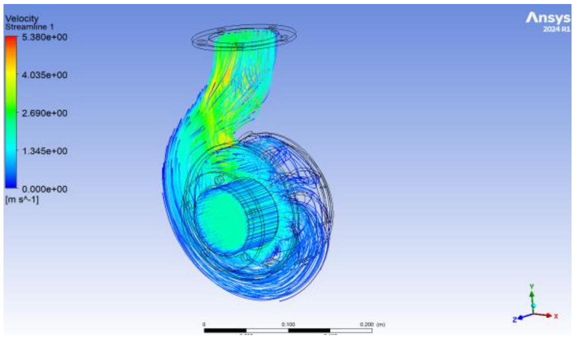


Fig. No. 6.14: Velocity streamline of Centrifugal Pump with existing impeller.

6.3 Modal Analysis of Slotted Blade Impeller

1. Geometry:

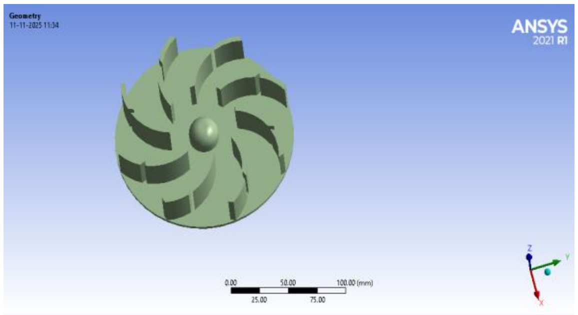
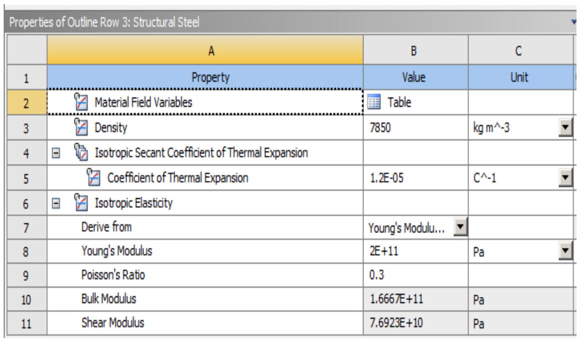


Fig No.6.15: Geometry of slotted blade impeller.

2. Material Properties:

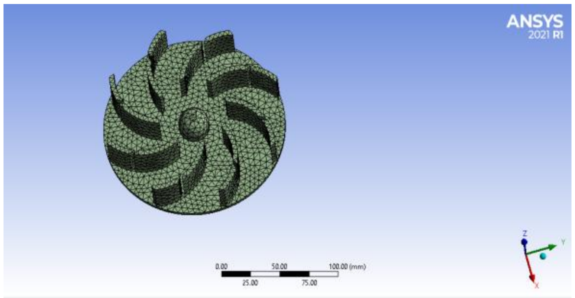


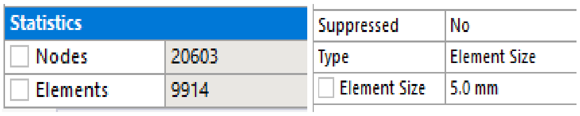
Properties of Outline Row 3: Structural Steel

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	7850	kg m^-3
4	⊟ Isotropic Secant Coefficient of Thermal Expansion		
5	Coefficient of Thermal Expansion	1.2E-05	C^-1
6	⊟ Isotropic Elasticity		
7	Derive from	Young's Modulu...	
8	Young's Modulus	2E+11	Pa
9	Poisson's Ratio	0.3	
10	Bulk Modulus	1.6667E+11	Pa
11	Shear Modulus	7.6923E+10	Pa

Fig No.6.16: Material Properties of Structural steel.

3. Meshing:





Statistics	
Nodes	20603
Elements	9914

Suppressed	No
Type	Element Size
Element Size	5.0 mm

Fig No.6.17: Meshing Details of slotted blade impeller.

4. Boundary Conditions:

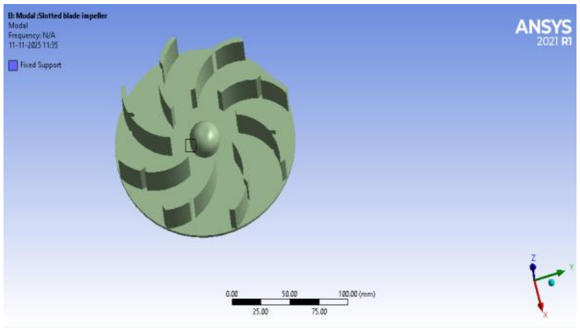


Fig No.6.18: Boundary conditions for modal analysis of slotted blade impeller.

5. Results:

a) Mode Shape 1:

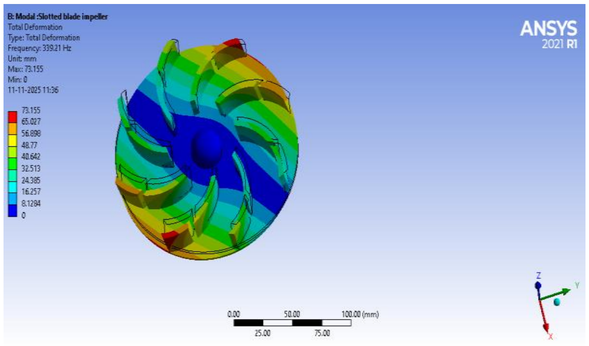


Fig No.6.19: Total Deformation for Mode Shape 1 for slotted blade impeller.

b) Mode Shape 2:

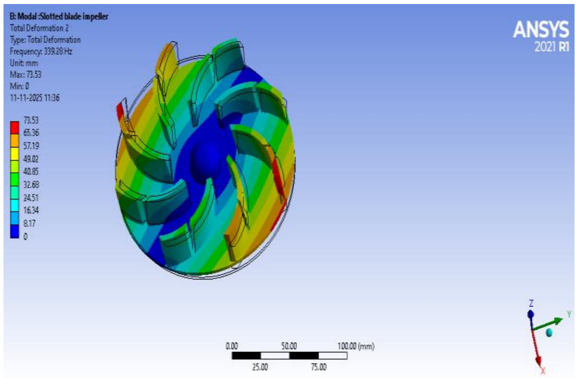


Fig No.6.20: Total Deformation for Mode Shape 2 for slotted blade impeller.

c) Mode Shape 3:

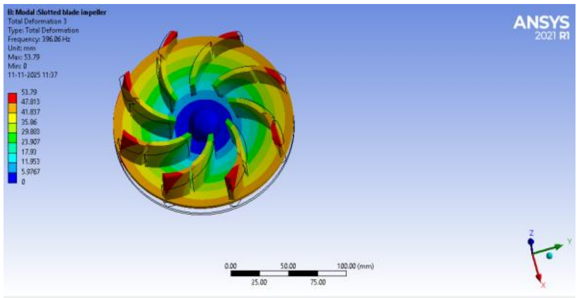


Fig No.6.21: Total Deformation for Mode Shape 3 for slotted blade impeller.

d) Mode Shape 4:

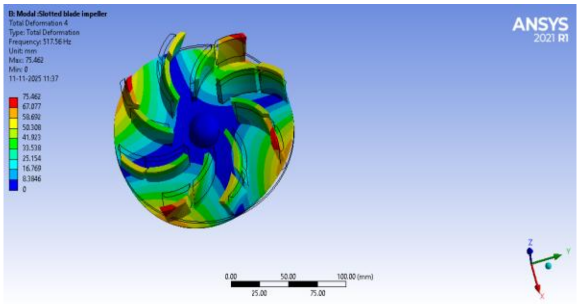


Fig No.6.22: Total Deformation for Mode Shape 4 for slotted blade impeller.

e) Mode Shape 5:

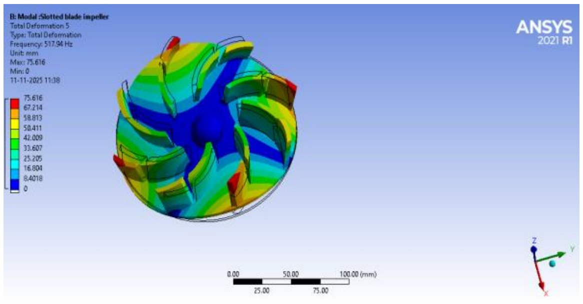


Fig No.6.23: Total Deformation for Mode Shape 5 for slotted blade impeller.

f) Mode Shape 6:

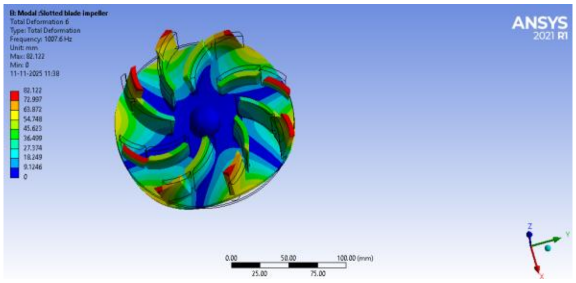
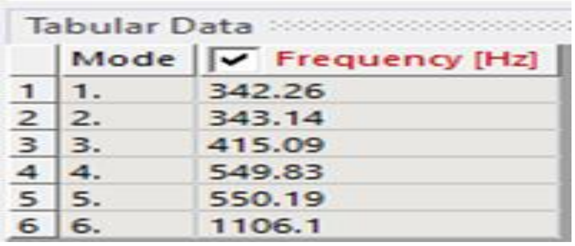


Fig No.6.24: Total Deformation for Mode Shape 6 for slotted blade impeller.



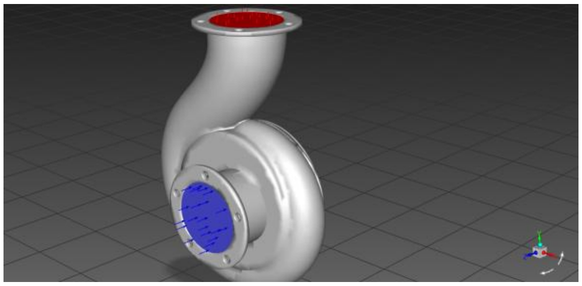
Tabular Data

	Mode	✓ Frequency [Hz]
1	1.	342.26
2	2.	343.14
3	3.	415.09
4	4.	549.83
5	5.	550.19
6	6.	1106.1

Table. 6.2: Mode no. and their frequencies for slotted blade impeller.

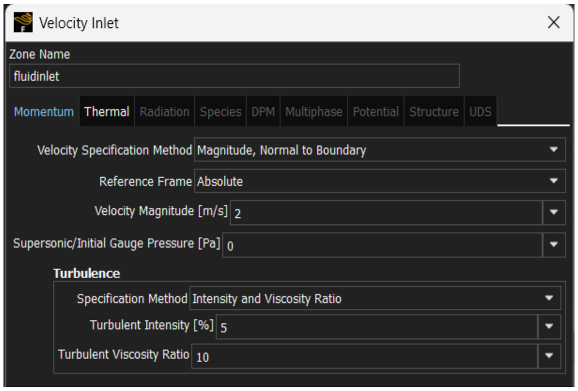
6.4 Fluent Analysis of Centrifugal Pump with Slotted Blade Impeller

1. Boundary Conditions:



Models

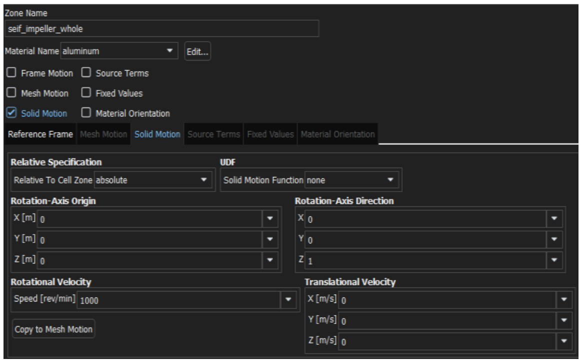
Multiphase - Off
Energy - On
Viscous - SST k-omega



Zone Name
fluidinlet

Velocity Specification Method: Magnitude, Normal to Boundary
Reference Frame: Absolute
Velocity Magnitude [m/s]: 2
Supersonic/Initial Gauge Pressure [Pa]: 0

Turbulence
Specification Method: Intensity and Viscosity Ratio
Turbulent Intensity [%]: 5
Turbulent Viscosity Ratio: 10



Zone Name
seif_impeller_whole
Material Name: aluminum

☐ Frame Motion ☐ Source Terms
☐ Mesh Motion ☐ Fixed Values
☑ Solid Motion ☐ Material Orientation

Relative Specification
Relative To Cell Zone: absolute

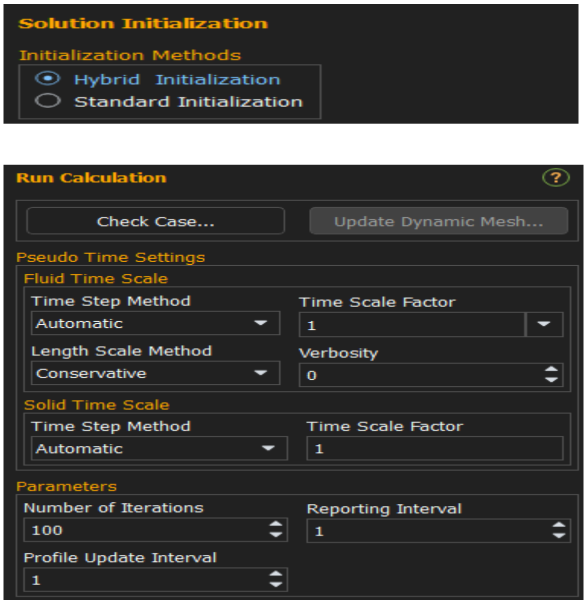
UDF
Solid Motion Function: none

Rotation-Axis Origin
X [m]: 0
Y [m]: 0
Z [m]: 0

Rotation-Axis Direction
X: 0
Y: 0
Z: 1

Rotational Velocity
Speed [rev/min]: 1000

Translational Velocity
X [m/s]: 0
Y [m/s]: 0
Z [m/s]: 0



Solution Initialization

Initialization Methods

● Hybrid Initialization
○ Standard Initialization

Run Calculation

Pseudo Time Settings

Fluid Time Scale

Time Step Method: Automatic
Time Scale Factor: 1
Length Scale Method: Conservative
Verbosity: 0

Solid Time Scale

Time Step Method: Automatic
Time Scale Factor: 1

Parameters

Number of Iterations: 100
Reporting Interval: 1
Profile Update Interval: 1

Fig. No. 6.25: Boundary conditions for fluent analysis of centrifugal pump with slotted blade impeller.

2. Results:

a) Pressure Contour:

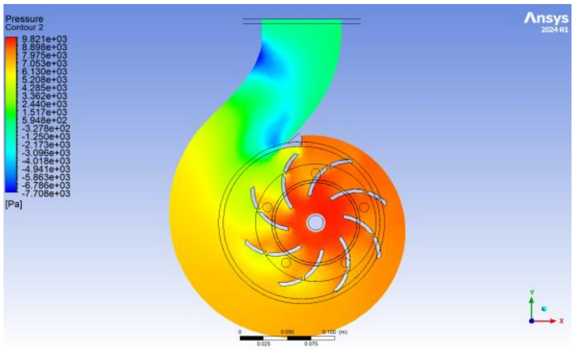


Fig. No. 6.26: Pressure contour of Centrifugal pump with existing impeller.

b) Velocity Contour:

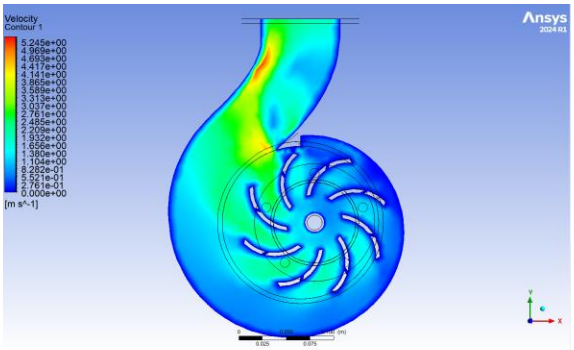


Fig. No. 6.27: Velocity contour of Centrifugal Pump with existing impeller.

c) Velocity Streamline:

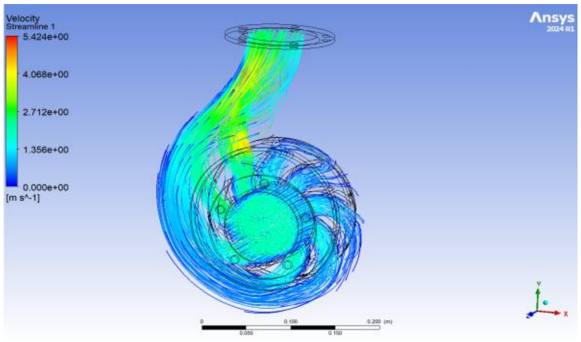


Fig. No. 6.27: Velocity streamline of Centrifugal Pump with existing impeller.

6.5 Fea Results

Mode shape	Normal blade impeller (MS) Natural frequency (HZ)	Slotted blade impeller (MS) Natural frequency (HZ)
1	342.26	339.21
2	343.14	339.28
3	415.09	396.06
4	549.83	517.56
5	550.19	517.94
6	1106.1	1007.6

Table No.6.3: FEA Results

CFD simulations were performed using ANSYS Fluent to evaluate the hydraulic performance of the conventional impeller and the proposed slotted blade impeller. The analysis focused on the distribution of pressure, velocity fields, and streamline patterns within the pump domain to assess the influence of blade slotting on internal flow behavior.

1. Pressure Field Analysis

The pressure contour for the conventional impeller shows a gradual increase in pressure from the suction region toward the volute outlet, reaching a maximum value of approximately 9.99 × 10^3 Pa. This pressure rise reflects the effective transfer of mechanical energy from the rotating impeller to the working fluid. However, localized pressure gradients are observed around certain blade passages and near the trailing edges, indicating complex flow interactions within the impeller channels.

In the slotted blade impeller configuration, the pressure distribution appears comparatively more uniform across the impeller passages and the volute casing. The slot structure enables partial redistribution of fluid between adjacent flow channels, which reduces localized pressure concentration and promotes smoother pressure variation throughout the pump. This behavior indicates improved internal energy transfer and more stable hydraulic conditions.

2. Velocity Field Analysis

The velocity contour of the conventional impeller indicates a maximum velocity of approximately 5.34 m/s, occurring mainly near the volute throat region where the fluid exits the impeller. Lower velocity regions are observed near the hub and inner blade passages, suggesting uneven flow distribution and the possibility of localized flow disturbances.

For the slotted blade impeller, the velocity field demonstrates improved uniformity across the flow passages. The presence of blade slots facilitates controlled fluid interaction between adjacent channels, which contributes to smoother velocity gradients and improved flow continuity. The maximum velocity observed is approximately 5.25 m/s, while the overall velocity distribution shows reduced fluctuations compared to the conventional configuration.

3. Streamline Analysis

Streamline visualization provides further insight into the flow behavior inside the pump. In the conventional impeller, the fluid follows the expected centrifugal path from the suction inlet to the volute outlet, although minor flow irregularities are visible near blade surfaces and casing boundaries.

In contrast, the slotted blade impeller exhibits smoother and more organized streamline patterns. The slots assist in guiding the flow more effectively through the impeller passages, allowing improved fluid movement toward the volute outlet. The resulting streamline distribution indicates enhanced flow stability and more efficient fluid transport within the pump.

4. Modal Analysis

A modal analysis was performed using finite element methods to evaluate the structural dynamic characteristics of the impellers. The natural frequencies and corresponding mode shapes were obtained for multiple vibration modes.

The analysis showed that variations in blade number did not significantly affect the modal frequencies of the impellers. Both the conventional and slotted blade configurations exhibited consistent dynamic characteristics. The slotted blade impeller maintained stable modal behavior, confirming that the structural integrity of the impeller is preserved while incorporating the slot design.

VII. EXPERIMENTAL ANALYSIS

7.1 The Process of Experimental Analysis

Fast Fourier Transform

Gauss introduced critical factorisation in 1805, whereas Cooley and Turkey (1965) studied FFTs. The Danielson-Lanczos lemma allows an FFT to do a discrete Fourier transform with a power of two points. If the number of points is not a power of two, N's prime factors can be transformed slightly slower. An efficient real Fourier transform or fast Hartley transform doubles speed (Bracewell 1999). Base-4 and base-8 rapid Fourier transforms are 20-30% faster than base-2 using optimised code. For N=2, 3, 4, 5, 7, 8, 11, 13, and 16, Winograd transform speeds discrete Fourier transformations. Slow prime factorisation with huge factors.

FFTs verify experiments. The FFT spectrum analyser samples the input signal, computes sine and cosine magnitudes, and displays their spectrum. Speed is a benefit of this strategy. FFT spectrum analysers measure all frequency components at once, making them hundreds of times faster than analogue ones.

Fourier analysis of a periodic function yields sines and cosines that replicate it when superimposed. A Fourier series shows this. The quick Fourier transform mathematically transfers time to frequency. Sometimes time becomes frequency. Helps analyse time-dependent phenomena.

Impact Hammer Test

Impact excitation is a common experimental modal testing method. Hammer impacts generate a broad banded excitation signal for modal testing with minimal setup. It's portable, versatile, and accurate. Weaknesses include accurate placement and force level control, but its benefits make it perfect for many modal testing situations.

Impulse testing using FFT signal processing demands careful data collection for spectrum functions. The input and output signals' finite samples cause issues. Lightly damped buildings may respond slowly to hammer strikes, making signal capture difficult.

Spectral bias problems from the truncation effect may affect estimated spectra. The computational and hardware restrictions of FFT processing devices worsen signal truncation. Operators frequently have several data capture durations or frequency ranges to choose from. Users value analysis frequency above data capture length. Therefore, an incorrect data acquisition length could truncate the vibration signal and create estimated spectra errors. Truncation is usually suppressed by force. Exponentially multiplying the slowly declining vibration signal artificially diminishes it. Be careful with the exponential window, which can damage approximated spectra.

Double hits are common in impact testing. A double impact offers the structure two impulses, one immediate and one delayed. Time and spectral characteristics of double hit input and output differ substantially from single hits. Double hits lack single hits' wide-band constant input force spectrum. This research examines how traditional FFT signal processing limits impact vibration testing. The impact testing technique is evaluated using analytical time and spectrum functions for an idealised test a single-degree-of-freedom system triggered by a half sine impact force. Examine structural impact testing conditions after knowing the fundamental characteristics. We compare system settings to data capture demands. We examine exponential windowing's effects on estimated spectra and modal parameters. The double hit phenomena is studied using data from the single degree-of-freedom system generated by two impulses, one of which is time delayed. Combining these studies gives structural impact testing data collection standards.

7.2 Experimental Testing

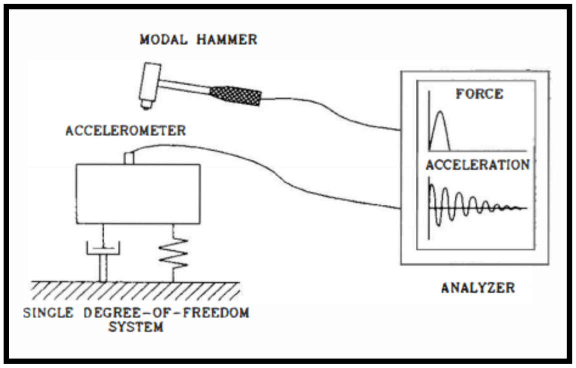


Fig. No. 7.1: FFT construction.

Fig. No.7.2: Experimental Testing Setup

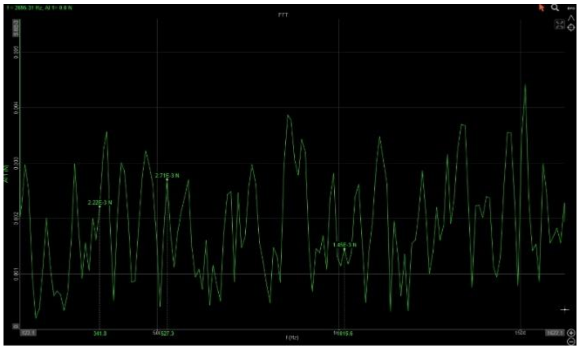


Fig. No.7.3: Specimen FFT Testing Graph

7.3 Experimental Testing Results

Results:

Mode Shape	Natural Frequency Slotted Blade Impeller (FEA)	Natural Frequency Slotted Blade Impeller (FFT)
1	339.21	341.6
2	339.28	341.6
3	396.06	341.6
4	517.56	527.3
5	517.94	527.3
6	1007.6	1015.6

Table No.7.1: Experimental Testing Results.

VIII. CONCLUSION

This study investigated the hydraulic and structural performance of a slotted blade impeller for a centrifugal pump through computational analysis. CFD results demonstrated that the introduction of blade slots improves internal flow characteristics by promoting a more uniform pressure distribution and smoother velocity profiles within the impeller passages.

The streamline analysis confirmed that the slotted blade configuration enhances flow guidance and stability, enabling more effective fluid movement from the suction inlet to the volute outlet. These improvements indicate the potential of the slotted blade design to enhance hydraulic performance and optimize pump operation.

In addition, modal analysis confirmed that the structural dynamic behavior of the impeller remains stable with the introduction of blade slots. The natural frequencies and mode shapes obtained from the analysis demonstrate that the slotted blade design maintains structural reliability while offering improved hydraulic characteristics.

Overall, the results indicate that the slotted blade impeller represents a promising design modification for improving centrifugal pump performance. Future research will focus on experimental validation and further optimization of slot geometry to achieve enhanced hydraulic efficiency and operational effectiveness.

IX. FUTURE SCOPE

Furthermore, research gaps remain regarding the intricate dynamics of bubble interactions and the overall optimization of full-scale systems. Future work could explore refining the Eulerian-Eulerian modelling approach to better capture gas-liquid behaviors across a wider range of bubble sizes and rotational speeds to prevent cavitation. Additionally, expanding this "active flow field control" concept to other centrifugal pump components or multistage configurations could further enhance the reliability and efficiency of artificial lift technologies in gas-rich oil wells.

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