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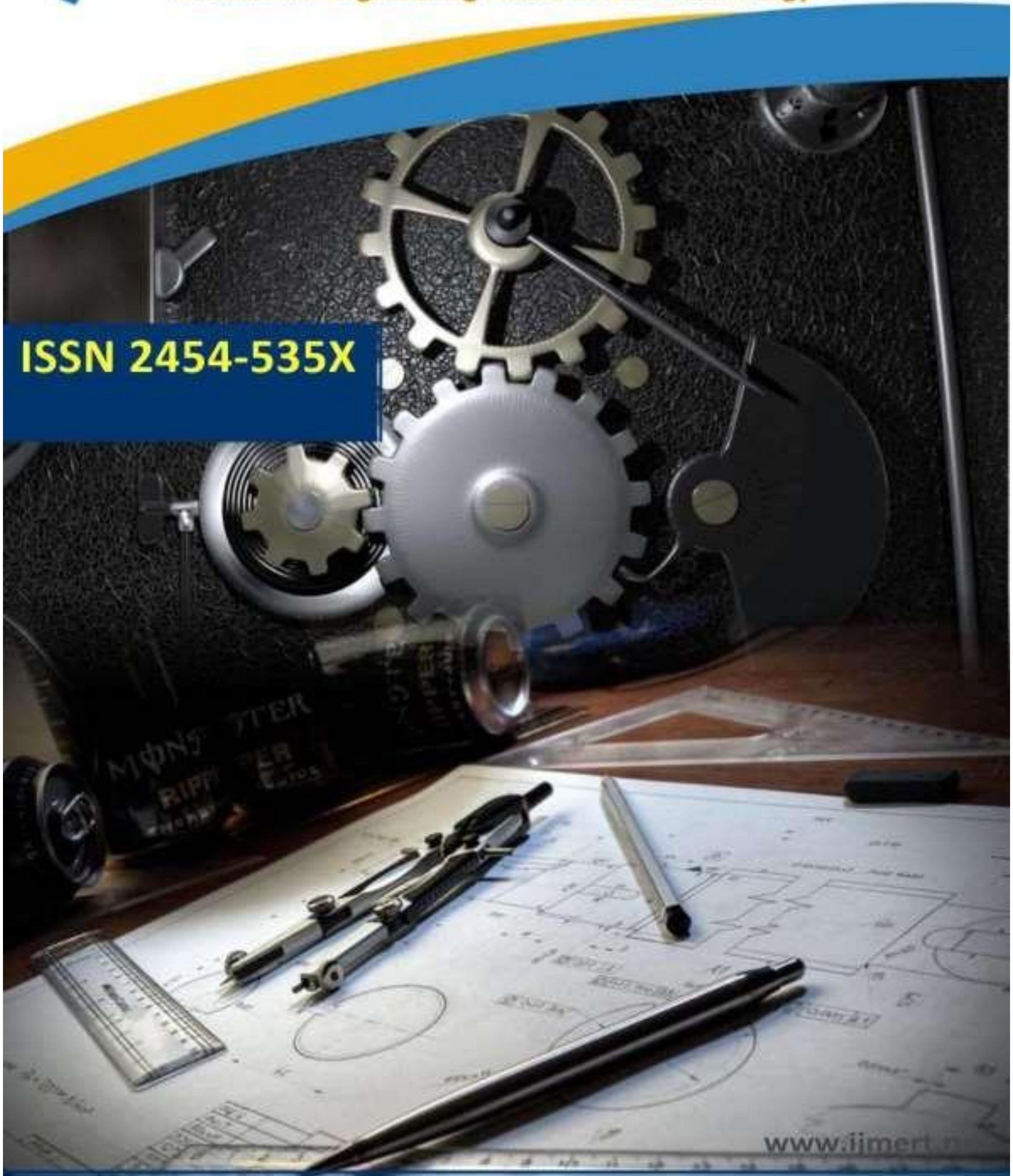

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SIMULATION-BASED NONLINEAR PRESTRESSED MODAL ANALYSIS OF A STRUCTURE (IMPELLER PUMP) USING ANSYS

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ABSTRACT

Impeller-type pumps are widely used in fluid-handling systems where structural stiffness and elastic integrity under operational loading are critical. This study presents a linear static structural analysis of a five-component impeller pump assembly subjected to a 100 N belt-equivalent bearing load. The objectives are to verify that impeller deflection remains below the allowable limit of 0.075 mm and to ensure that the Polyethylene pump housing operates within its elastic limit, particularly near the shaft bore where stress concentration is expected.

1. INTRODUCTION

Pump assemblies must maintain:

- Dimensional stability
- Adequate stiffness
- Elastic structural behavior
- Proper load transfer

Belt-driven pumps experience radial loading transmitted from pulley to shaft and into the housing. Improper stiffness or excessive deformation can lead to:

- Rotor–stator interference
- Reduced hydraulic efficiency

- Increased vibration
- Housing cracking

Finite Element Analysis (FEA) provides a systematic method to predict deformation and stress behavior under such loading conditions.

2. THEORETICAL BACKGROUND

2.1 Linear Static Structural Analysis

Linear static analysis assumes:

- Linear elastic material behavior
- Small deformations
- Static loading
- Proportional load–response relationship

The governing FEM equilibrium equation is:

$$[K]\{u\} = \{F\}$$

Where:

- K= global stiffness matrix
- u= nodal displacement vector
- F= applied force vector

2.2 Stress–Strain Relationship

For linear elastic materials:

$$\sigma = E\varepsilon$$

Where:

- E= Young's modulus
- σ= stress
- ε= strain

2.3 Von Mises Failure Criterion

For multiaxial stress states, equivalent stress:

$$\sigma_{vm} = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}$$

Safety condition:

$$\sigma_{vm} < \sigma_{yield}$$

2.4 Deformation Limit Criterion

Impeller allowable deflection:

$$\delta_{max} = 0.075 \text{ mm}$$

Structural stiffness:

$$k = \frac{F}{\delta}$$

Literature Review

Linear static structural analysis has been widely adopted in engineering practice for evaluating the structural integrity of mechanical components subjected to steady loading conditions. Several researchers have demonstrated that finite element solvers such as **ANSYS Mechanical** provide reliable predictions of stress and deformation when the assumptions of **linear elasticity, small strains, and static equilibrium** are satisfied. Under these assumptions, the governing equations reduce to a linear system relating nodal forces and displacements, enabling efficient and robust analysis of complex assemblies.

3. MATERIALS

3.1 Pump Housing – Polyethylene

- Yield Strength: 25 MPa
- Linear elastic behavior assumed
- Isotropic and homogeneous

Housing stress must remain below 25 MPa.

Polyethylene

Density	950 kg/m³
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	1.1e+09 Pa
Poisson's Ratio	0.42
Bulk Modulus	2.2917e+09 Pa
Shear Modulus	3.8732e+08 Pa
Isotropic Secant Coefficient of Thermal Expansion	0.00023 1/°C
Compressive Ultimate Strength	0 Pa
Compressive Yield Strength	0 Pa
Tensile Ultimate Strength	3.3e+07 Pa
Tensile Yield Strength	2.5e+07 Pa
Thermal	
Isotropic Thermal Conductivity	0.28 W/m·°C
Specific Heat Constant Pressure	2300 J/kg·°C

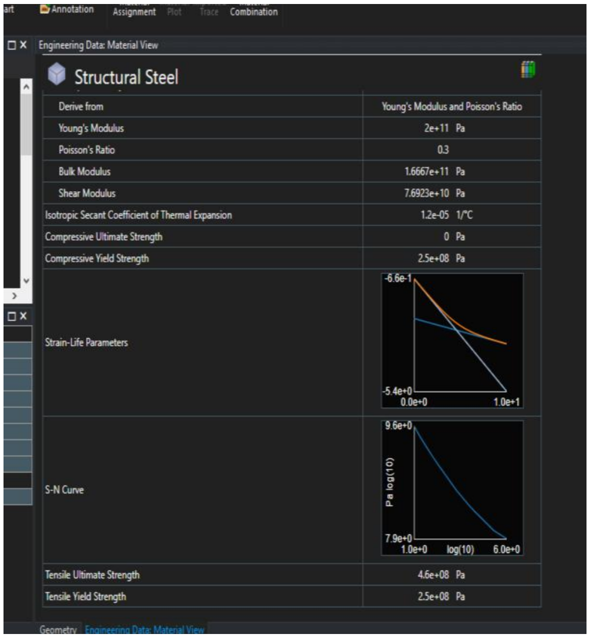
3.2 Metallic Components

Impeller, shaft, pulley, and nut modeled as linear elastic metallic solids.

Assumptions:

- Stress << metal yield strength
- No plastic deformation
- Rigid-like behavior relative to housing

The assumption of linear elastic behavior for metallic parts is justified because the applied **100 N belt load** induces stress levels well below typical yield strengths of engineering metals. As a result, nonlinear material effects such as plastic yielding are not expected, and linear elastic modeling provides sufficient accuracy for global structural analysis.



Structural Steel

Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	2e+11 Pa
Poisson's Ratio	0.3
Bulk Modulus	1.6667e+11 Pa
Shear Modulus	7.6923e+10 Pa
Isotropic Secant Coefficient of Thermal Expansion	1.2e-05 1/°C
Compressive Ultimate Strength	0 Pa
Compressive Yield Strength	2.5e+08 Pa
Strain-Life Parameters	
S-N Curve	
Tensile Ultimate Strength	4.6e+08 Pa
Tensile Yield Strength	2.5e+08 Pa

Structural steel

4. GEOMETRY AND MODELING

The geometric model used in this study is imported into **ANSYS Workbench** as a three-dimensional **STEP file** named *"Pump_assy_3.stp"*. The geometry represents a complete **five-body pump assembly**, consisting of an **impeller, pump**

housing, pulley, shaft, and retaining nut. Each component is modeled as a separate solid body to enable independent material assignment and accurate representation of load transfer between parts.

Geometry imported as:

Pump_assy_3.stp

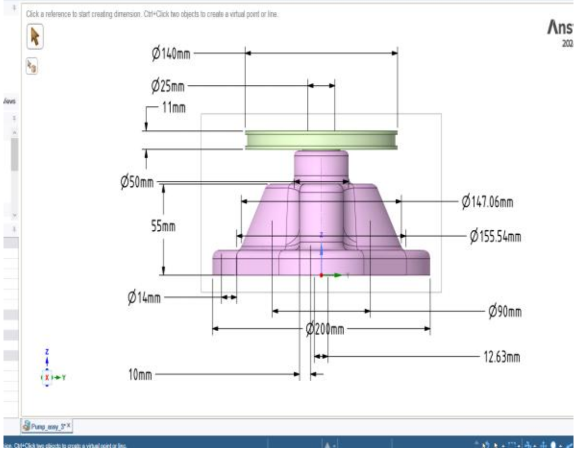
Assembly consists of:

- Impeller
- Housing
- Shaft
- Pulley
- Nut

All bodies modeled separately to enable contact definition.

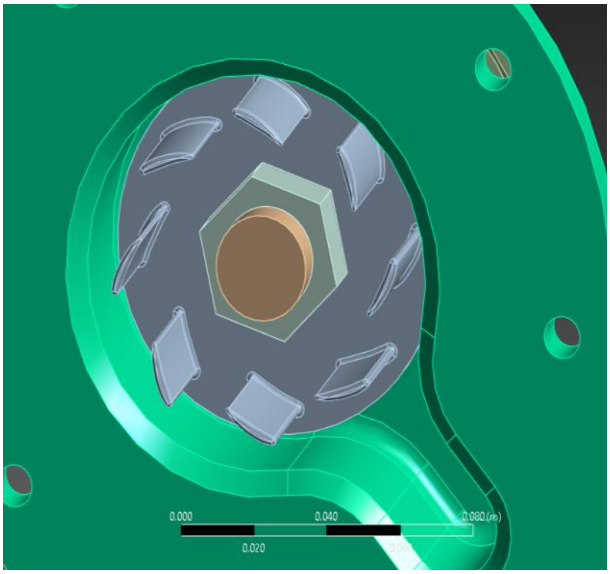
Unit system:

- Length: mm
- Force: N
- Mass: kg

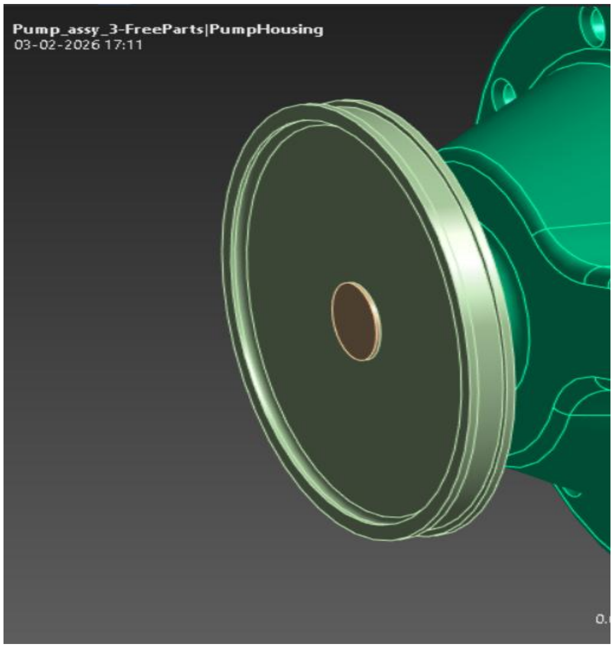


Click a reference to start creating dimension. Ctrl+Click two objects to create a virtual point or line.

Pump Assembly



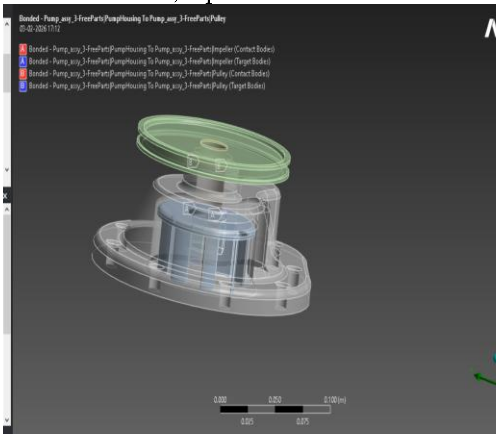
Impeller blades



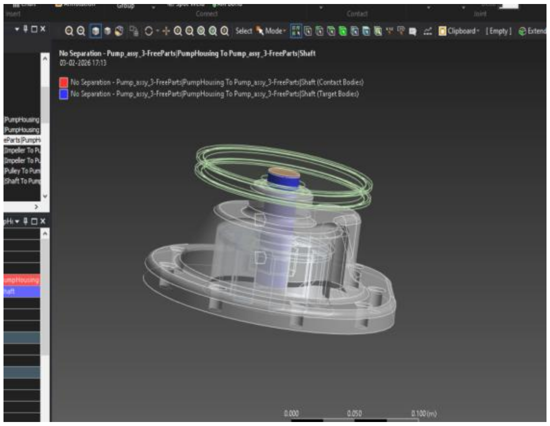
Pulley

5. CONTACT DEFINITIONS

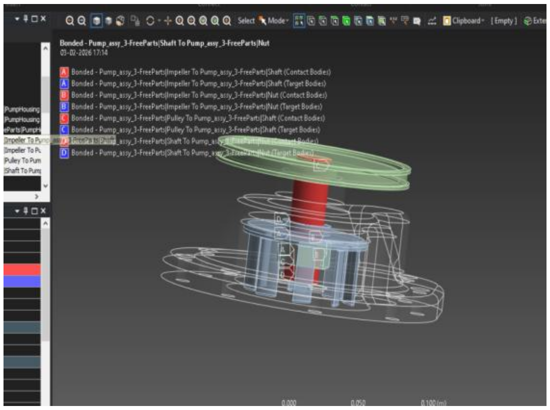
Accurate modeling of contact interactions is critical in multi-body assemblies. In the present study, contact interfaces between components such as shaft–housing, shaft–impeller, pulley–shaft, and nut–shaft are defined using **idealized contact formulations** available in ANSYS Mechanical.



Pump assembly bonded connection



Pump housing No Separation contact



Pump assembly to blades contact

Interfaces modeled as:

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- Bonded contacts (shaft–impeller, pulley–shaft)
- No-Separation contact (shaft–housing)

This ensures:

- Realistic load transfer
- Maintains linearity
- Avoids artificial stiffness

6. MESHING STRATEGY

6.1 Coarse Mesh

- Automatic sizing
- Captures global deformation
- Limited stress resolution

6.2 Refined Mesh

Local refinement near:

- Shaft bore
- Mounting regions
- Contact interfaces

Improves stress gradient resolution.

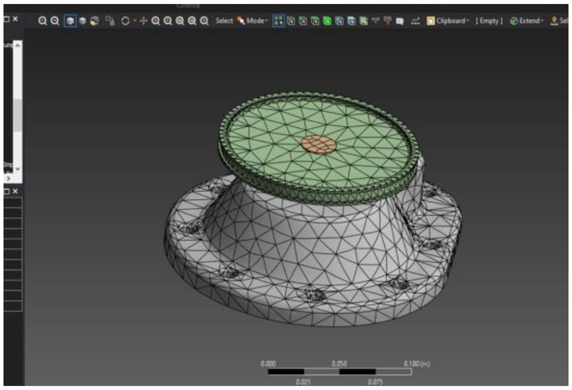
Initial Coarse Mesh Strategy

An initial **default, relatively coarse mesh** is generated automatically by ANSYS Mechanical for the entire assembly. The primary purpose of this mesh is to capture the **global stiffness response** and overall deformation pattern of the structure with minimal computational effort.

At this stage:

- Automatic element sizing is used
- No local mesh controls are applied
- The mesh resolves major geometric features but does not fully capture local stress concentrations

Such a coarse mesh is appropriate for an introductory analysis, as it allows rapid identification of load paths, boundary condition correctness, and overall deformation trends before investing computational resources in mesh refinement.



Coarse mesh

7. BOUNDARY CONDITIONS

7.1 Supports

Frictionless supports applied on:

- Housing mounting face
- Countersink surfaces

Prevents rigid-body motion.

Weak springs disabled.

Housing Mounting Face Constraint

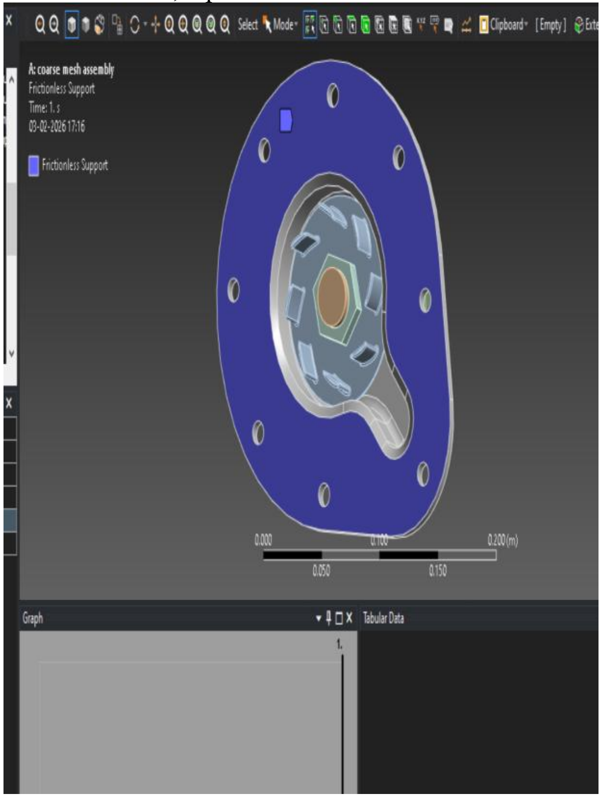
The primary structural constraint is applied on the **pump housing mounting face**, which is assumed to be rigidly attached to a base or supporting structure. This interface is modeled using a **frictionless support** in ANSYS Mechanical.

A frictionless support:

- Restrains displacement **normal to the surface**
- Allows **free tangential motion** along the surface

This boundary condition effectively represents a rigid backing that prevents penetration while avoiding artificial in-plane stiffness. The choice of frictionless support is particularly suitable when the mounting interface is stiff in the normal direction but does not significantly restrict in-plane deformation.

This modeling approach prevents over-constraining the housing and ensures that stress development is governed by applied loads rather than artificial boundary stiffness.



Frictionless face

6.2.2 Mounting Hole Constraints (Countersink Surfaces)

Additional constraints are applied to the **eight countersink surfaces of the housing mounting holes**, representing the presence of mounting bolts. These surfaces are also assigned **frictionless supports**, which simulate contact between the bolt heads and the housing without explicitly modeling bolt shanks, threads, or preload.

Applying frictionless supports at these locations:

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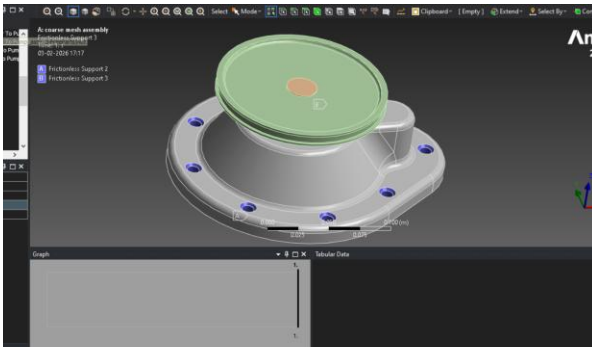
- Distributes reaction forces realistically across multiple mounting points
- Prevents excessive local deformation at a single constraint location
- Improves numerical stability of the solution

To efficiently select these surfaces, **Named Selections based on geometric size** or ANSYS “select by size” macros are used. This ensures consistent and repeatable selection of small but critical surfaces, reducing the risk of modeling errors.


A: coarse mesh assembly
Frictionless Support 3
Time: 1. s
03-02-2026 17:17
A Frictionless Support 2
B Frictionless Support 3

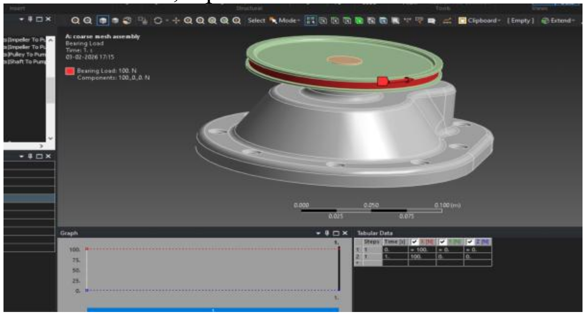
Frictionless counter sink

7.2 Bearing Load

100 N applied on pulley groove:

- Direction: Global X-axis
- Distributed using bearing load feature

Ensures realistic shaft bending.

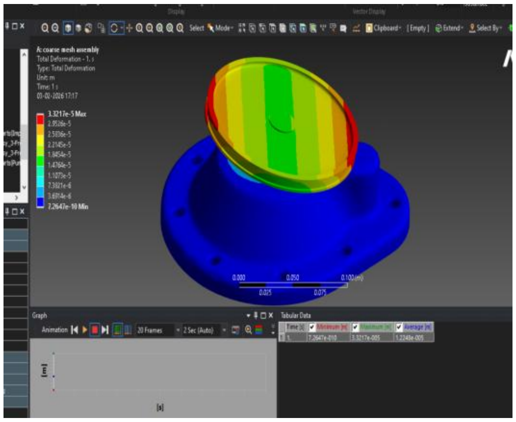

A: coarse mesh assembly
Bearing Load
Time: 1. s
03-02-2026 17:15
Bearing Load: 100. N
Components: 100.,0.,0. N

Bearing load

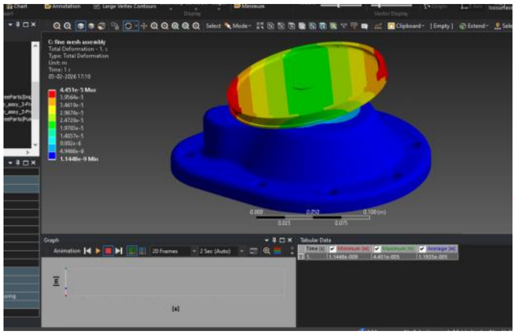
8. RESULTS

Global Results (Assembly-Level Response)

Initial post-processing is performed on the complete pump assembly to obtain a holistic understanding of the structural response under the applied 100 N bearing load on the pulley.


A: coarse mesh assembly
Total Deformation - 1. s
Type: Total Deformation
Unit: m
Time: 1 s
03-02-2026 17:17

Deformation coarse mesh



Deformation fine mesh

8.1 Impeller Deformation

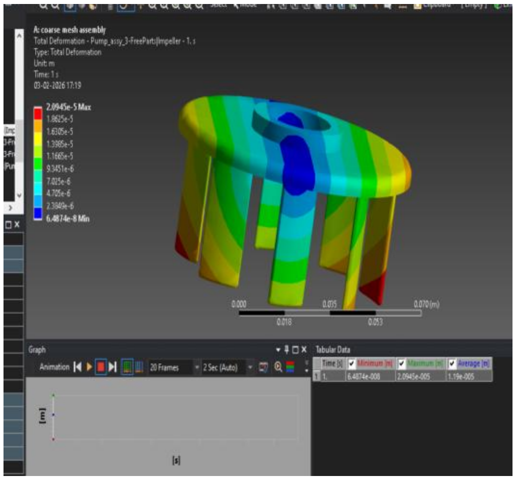
Maximum impeller deformation:

$$\delta_{impeller} \approx 0.022 \text{ mm}$$

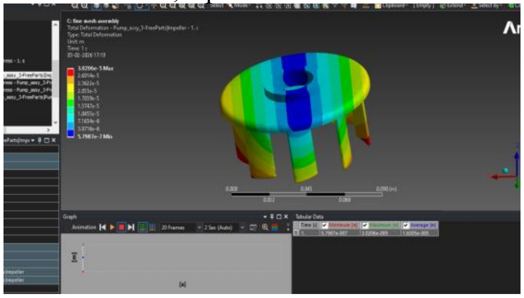
Comparison:

Allowable	**Obtained**
0.075 mm	0.022 mm

✓ Within acceptable limit.



Impeller coarse



Impeller fine mesh

8.2 Housing Stress

Maximum von Mises stress (coarse mesh):

4 MPa

Maximum von Mises stress (fine mesh):

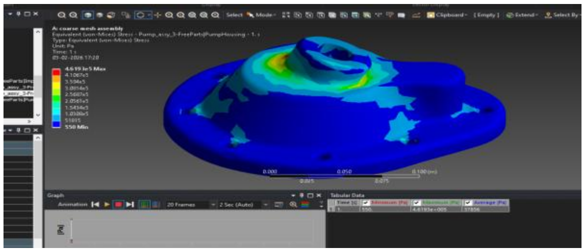
1.2 MPa

Yield strength:

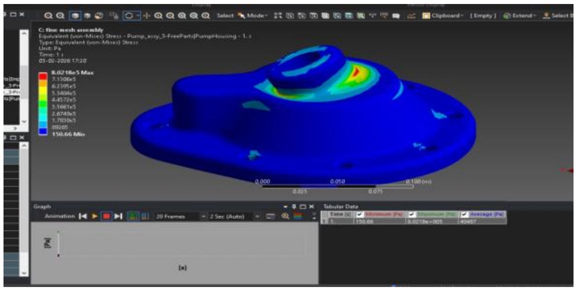
25 MPa

Safety condition satisfied.

The maximum von Mises stress in the housing remains **below the tensile yield strength of 25 MPa** specified for the Polyethylene material. This confirms that the pump housing operates entirely within its elastic regime for the given loading scenario, with no risk of yielding or permanent deformation. Consequently, the housing design is deemed structurally safe for the considered static load case.



Equivalent stress coarse



Equivalent stress fine mesh

8.3 Mesh Comparison Table

Stress Results

Mesh Type	**Equivalent Stress (MPa)**
Coarse	4
Fine	1.2

Deformation Results

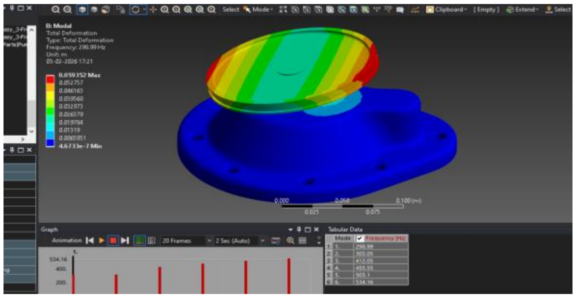
Mesh	**Deformation 1 (mm)**	**Deformation 2 (mm)**	**Deformation 3 (mm)**
Coarse	0.06	0.058	0.04
Fine	0.058	0.057	0.038

Observation:

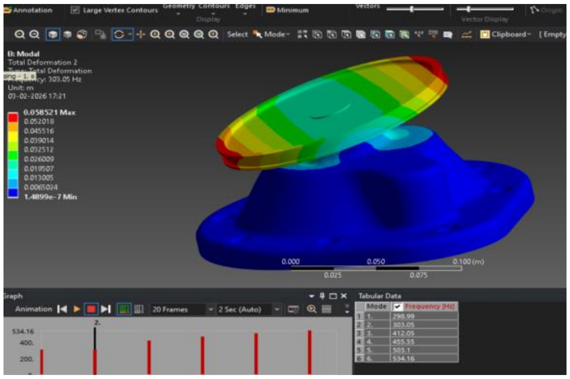
- Deformation converges quickly
- Stress more mesh-sensitive

7.4 Effect of Mesh Refinement on Results

To study mesh sensitivity and result convergence, local mesh refinement is applied in stress-critical regions such as the pump housing near the shaft bore and mounting features. After refining the mesh and re-solving the model, both deformation and stress results show noticeable changes.



Deformation 1 coarse



Deformation 2 coarse

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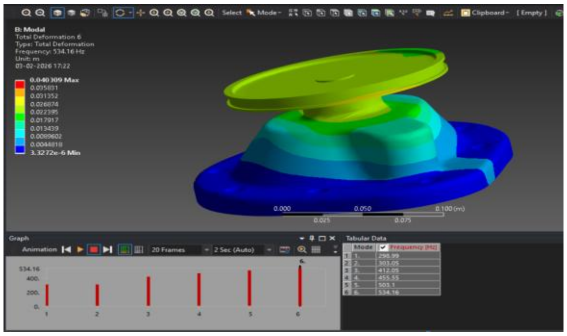
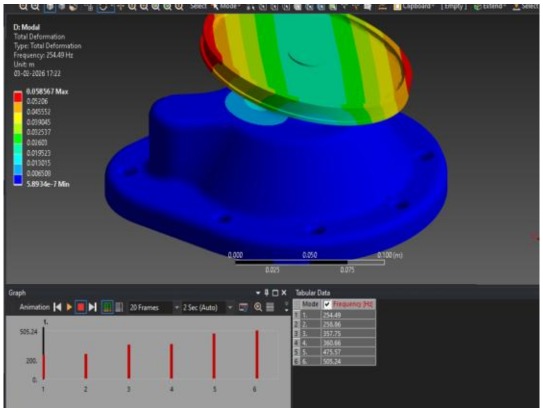


B: Modal
Total Deformation 6
Type: Total Deformation
Frequency: 534.16 Hz
Unit: m
03-02-2026 17:22

	Mode	Frequency [Hz]
1	1.	298.99
2	2.	303.05
3	3.	412.05
4	4.	455.55
5	5.	503.1
6	6.	534.16

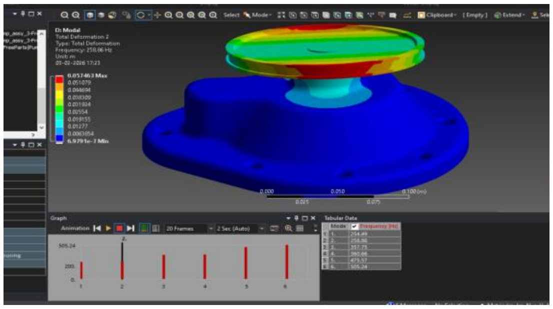
Deformation 3 coarse



D: Modal
Total Deformation
Type: Total Deformation
Frequency: 254.49 Hz
Unit: m
03-02-2026 17:22

	Mode	Frequency [Hz]
1	1.	254.49
2	2.	258.86
3	3.	357.75
4	4.	360.66
5	5.	475.57
6	6.	505.24

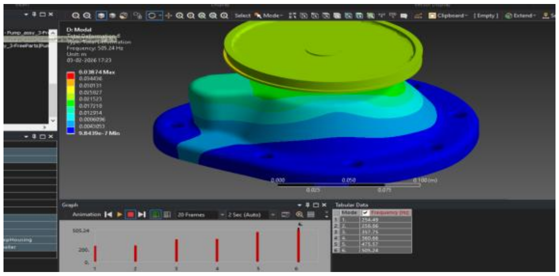
Deformation 1 fine mesh



D: Modal
Total Deformation 2
Type: Total Deformation
Frequency: 258.86 Hz
Unit: m
03-02-2026 17:23

	Mode	Frequency [Hz]
1	1.	254.49
2	2.	258.86
3	3.	357.75
4	4.	360.66
5	5.	475.57
6	6.	505.24

Deformation 2 fine mesh



D: Modal
Frequency: 505.24 Hz
Unit: m
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Deformation 3 fine mesh

9. DISCUSSION

Key findings:

- Load path verified correctly
- No rigid-body motion
- Impeller stiffness adequate
- Housing remains elastic
- Mesh refinement necessary for stress accuracy

Displacement converges faster than stress.

10. ENGINEERING SIGNIFICANCE

This analysis:

- Validates structural stiffness
- Ensures elastic safety
- Identifies stress concentration zones
- Provides foundation for advanced studies

Can be extended to:

- Nonlinear plasticity
- Fatigue analysis
- Rotational dynamics
- Fluid–structure interaction

12. CONCLUSION

The linear static structural analysis of the impeller pump assembly under a 100 N belt-equivalent load confirms:

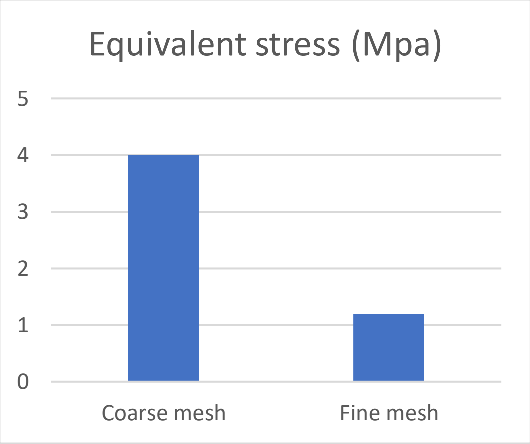
1. Maximum impeller deflection (0.022 mm) is well below the allowable limit (0.075 mm).
2. Housing stress remains below 25 MPa yield strength.
3. Assembly operates entirely within elastic regime.
4. Contact and boundary conditions produce realistic load paths.
5. Mesh refinement improves stress accuracy.

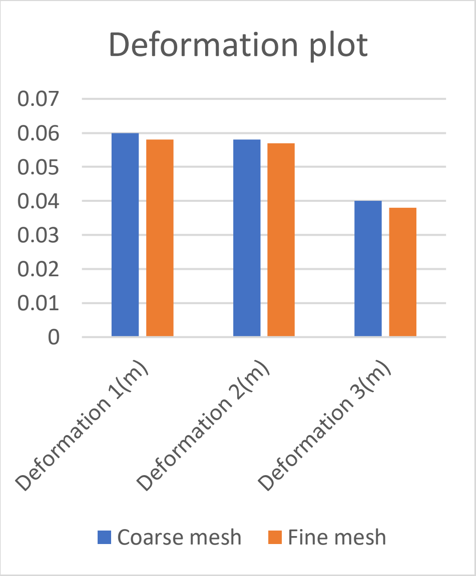
The pump assembly design is structurally adequate for the considered static loading case.

rotating machinery analyses to more closely replicate real operating conditions.

S.No	Parameter	Equivalent stress (Mpa)
1	Coarse mesh	4
2	Fine mesh	1.2

S. No	Parameter	Deformation 1(m)	Deformation 2(m)	Deformation 3(m)
1	Coarse mesh	0.06	0.058	0.04
2	Fine mesh	0.058	0.057	0.038





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