Linear Static and Dynamic Analysis of Impeller Type Centrifugal Pump with Different Materials

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Abstract:
This work deals with design of an Impeller type Centrifugal pump and do analysis using ANSYS WORK BENCH. The primary goal is to apply preload in the belt and to check deflections and stresses developed in impeller and pump housing. Different materials will be applied to pump and compared for internal induced stresses which should not exceed the elastic limit. The variation of von-misses stress, von-misses strain, deformation factor, natural frequencies, mode shapes for different materials can be taken into consideration. ANSYS DESIGN MODELER is used for modeling the parts and analysis is done in ANSYS WORKBENCH. ANSYS is dedicated finite element package used for determining the variation of stresses, strains and deformation across profile of the impeller. A structural analysis has been carried out to investigate the stresses, strains and displacements of the impeller.

Keywords: ANSYS work bench, Centrifugal pump, deformation factor, impeller, modal analysis, von-mises stress.

1. INTRODUCTION

A centrifugal pump is a kinetic device. Liquid entering the pump receives kinetic energy from the rotating impeller. The centrifugal action of the impeller accelerates the liquid to a high energy to the liquid. That kinetic energy is velocity, transferring mechanical (rotational) available to the fluid to accomplish work. In most cases, the work consists of the liquid moving at some velocity through a system by overcoming resistance to flow due to friction from pipes, and physical restrictions from valves, heat exchangers and other in-line devices, as well as elevation changes between the liquid's starting location and final destination. When velocity is reduced due to resistance encountered in the system, pressure increases. As resistance is encountered, the liquid expends some of its energy in the form of heat, noise, and vibration in overcoming that resistance. The result is that the available energy in the liquid decreases as the distance from the pump increases. The actual energy available for work at any point in a system is a combination of the available velocity and pressure energy at that point.

1.1 WORKING MECHANISM OF A CENTRIFUGAL PUMP

A centrifugal pump is one of the simplest pieces of equipment in any process plant. Its purpose is to convert energy of a prime mover (an electric motor or turbine) first into velocity or kinetic energy and then into pressure energy of a fluid that is being pumped. The energy changes occur by virtue of two main parts of the pump, the impeller and the volute or diffuser. The impeller is the rotating part that converts driver energy into the kinetic energy. The volute or diffuser is the stationary part that converts the kinetic energy into pressure energy.

Figure 1.1: working mechanism of a centrifugal pump

1.2 GENERAL COMPONENTS OF CENTRIFUGAL PUMP

A centrifugal pump has two main components:
I. A rotating component comprised of an impeller and a shaft
II. A stationary component comprised of a casing, casing cover, and bearings

1.3 PUMP HOUSING (or) CASING

Casings are generally of two types: volute and circular. The impellers are fitted inside the casings.

1.4 SHAFT

The basic purpose of a centrifugal pump shaft is to transmit the torques encountered when starting and during operation while supporting the impeller and other rotating parts. It must do this job with a deflection less than the minimum clearance between the rotating and stationary parts.
1.5 Impeller

The impeller is the main rotating part that provides the centrifugal acceleration to the fluid. They are often classified in many ways.

Based on major direction of flow in reference to the axis of rotation
- Radial flow
- Axial flow
- Mixed flow

Based on suction type
- Single-suction: Liquid inlet on one side.
- Double-suction: Liquid inlet to the impeller symmetrically from both sides.

Based on mechanical construction
- Closed: Shroud or sidewall enclosing the vanes.
- Open: No shrouds or wall to enclose the vanes.

1.6 TYPES OF IMPELLER:
- Open impeller
  - Enclosed impeller
  - Semi-open impeller

In this dissertation semi open type impeller is considered in design.

1.6.3 SEMI-OPEN IMPELLER

A semi-open impeller is a compromise between an open and an enclosed impeller. It incorporates a single shroud, usually located on the back of the impeller. A semi-open impeller has a solid spacing capability similar to that found in an open impeller. With only a single shroud a semi-open impeller is easy to manufacture and completely accessible for applying surface hardening treatments.

In this dissertation semi open type impeller is considered in design.

2. PROBLEM IDENTIFICATION

Most of the centrifugal pump impellers are made up with Mild Steel which has more density. This is main cause of high weight of pump. In addition to this it has high corrosion and less fatigue strength. The mild steel can be replaced with alloy material (e.g. structural steel, gray cast iron, polyethylene alloys) to reduce the weight, improve corrosion resistance and fatigue strength is more as compare to different alloys material and composite material. Due to less stiffness, deformations produced for the same material is more as compared to composite material and different alloys. In this project we will assemble 5 parts of an impeller of centrifugal pump. 1) Pump housing 2) Pulley 3) Shaft 4) Impeller 5) Nut. Our primary goal is to apply a preload of 100N in the belt and to check that impeller is not getting deflected to maximum of 0.0075 mm.

3. METHODOLOGY

PHASE1: Modeling of centrifugal pump
PHASE2: Analysis of impeller using ANSYS work bench
PHASE3: Analysis of pump housing using ANSYS
PHASE 4: Comparison of different load conditions for different materials.

3.1 EXPECTED OUTCOME

By analyzing and identifying the true design feature, the extended service life and long term stability is assured. By the comparison of the stresses for the two different loads can withstand the best material for the impeller can be chosen for manufacturing.

4. DESIGN DATA

Shaft dia (z1) = 25mm
Shaft length = 75mm
Pulley inner radius = 63mm
Pulley outside radius = 70mm
Pulley hub outer dia = 35mm
Pulley hub inner dia = 25mm
Pump housing outer circle dia = 100mm
Pump housing inner circle dia = 104.45mm
Pump housing holes dia = 10mm
Impeller hub inside dia = 25mm
Impeller hub outside dia = 35mm
Impeller blade height = 33mm
Nut dia = 25mm
Nut thickness = 15mm

5. FINITE ELEMENT APPROACH

5.1 GLOBAL STIFFNESS MATRIX

\[
\begin{bmatrix}
  f_1 \\
  f_2 \\
  f_3 \\
  f_4 \\
  f_5 \\
\end{bmatrix} = \begin{bmatrix}
  k_{11} & k_{12} & k_{13} & k_{14} & k_{15} \\
  k_{21} & k_{22} & k_{23} & k_{24} & k_{25} \\
  k_{31} & k_{32} & k_{33} & k_{34} & k_{35} \\
  k_{41} & k_{42} & k_{43} & k_{44} & k_{45} \\
  k_{51} & k_{52} & k_{53} & k_{54} & k_{55} \\
\end{bmatrix} \begin{bmatrix}
  u_1 \\
  u_2 \\
  u_3 \\
  u_4 \\
  u_5 \\
\end{bmatrix}
\]

Where, \( f \) = load vector, \( K \) = global stiffness matrix, \( U \) = displacement vector

In linear static analysis, the loads are applied gradually and slowly until they reach their full magnitude. After reaching their full magnitude, the loads remain constant (time-invariant). The accelerations and velocities of the excited system are negligible.
therefore, no inertial and damping forces are considered in the formulation:

\[
[K]\{u\} = \{f\}
\]

Where, \([K]\): stiffness matrix
\(\{u\}\): displacement vector
\(\{f\}\): load vector.

The solution produces displacements, stresses that are Constant.

**In linear dynamic analysis**, the applied loads are time-dependent. The loads can be deterministic (periodic, non-periodic), or non-deterministic which means that they cannot be precisely predicted but they can be described statistically. The accelerations and velocities of the excited system are significant, therefore, inertial and damping forces should be considered in the formulation

\[
[M]\ddot{u}(t) + [C]\dot{u}(t) + [K]u(t) = \{f(t)\}
\]

Where

\([K]\): stiffness matrix,
\([C]\): damping matrix
\([M]\): mass matrix
\(\{u(t)\}\): time varying displacement vector
\(\{\dot{u}(t)\}\): Time varying acceleration vector
\(\{\ddot{u}(t)\}\): Time varying velocity vector
\(\{f(t)\}\): time varying load vector

The response of the system is given in terms of time histories (amplitudes versus time), or in terms of frequency spectra (peak values versus frequency). For linear dynamic analysis, the mass, stiffness, and damping matrices do not vary with time. Material properties are assumed to be linear. Nonlinear dynamic studies must be used if material nonlinearity exists. In general, you can assume static conditions if the frequency of the loads is much lower than the lowest natural frequency of the system.

### 5.2 GEOMETRIC MODELLING

- **Figure 5.1**: pump with belt
- **Figure 5.2**: impeller
- **Figure 5.3**: Centrifugal pump parts
- **Figure 5.4**: Pump housing
- **Figure 5.5**: nut
TABLE 5.1 DIFFERENT MATERIALS PROPERTIES

<table>
<thead>
<tr>
<th>Material selected</th>
<th>Structural steel</th>
<th>High-density polyethylene</th>
<th>Gray Cast Iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>200 Gpa</td>
<td>1.1 Gpa</td>
<td>110 Gpa</td>
</tr>
<tr>
<td>Poison’s ratio</td>
<td>0.3</td>
<td>0.46</td>
<td>0.26</td>
</tr>
<tr>
<td>Density</td>
<td>7850 Kg/m³</td>
<td>950 Kg/m³</td>
<td>7200 Kg/m³</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>2.5E+8pa</td>
<td>2.5E+7 pa</td>
<td>2.8E+7pa</td>
</tr>
<tr>
<td>Tensile Ultimate shear Strength</td>
<td>4.6E+8pa</td>
<td>3.3E+7 pa</td>
<td>4.5E+7 pa</td>
</tr>
</tbody>
</table>

5.3 ANSYS PRE-PROCESSING

5.3.1 CONTACTS SETUP

Figure 5.6: Wheel

Figure 5.7: shaft

Figure 5.8: Bonded contact between pump housing to impeller

Figure 5.9: Bonded-pump housing to pulley

Figure 5.10: Bonded-pump housing to shaft

Figure 5.11: Bonded-pulley to shaft
5.4: ASSUMPTIONS

- Load is applied along x-direction only
- Temperature is considered to be 22°C.
- A frictionless support is assumed.

5.5 MESHING

Many different types of elements are available. Choice depends on the problem and the solver capabilities. In this work, the tetrahedral element is used for meshing.

- Element size 10 mm
- Face meshing - pump housing, element size - 5 mm.
- Body sizing - pulley, element size - 5 mm.
- Relevance - 50
- All tetrahedral mesh
6. RESULTS AND DISCUSSIONS

6.1. FOR 100N STRUCTURAL STEEL

6.1.1. TOTAL DEFORMATION

Figure 6.1: Max-0.039015 mm, Min-6.214e-9 mm

6.1.2. DEFORMATION ON IMPELLER

Figure 6.2: Max-0.00017839 mm, Min-1.7028e-6 mm

6.1.2. A) VON-MISES (EQUIVLENT) STRESS

6.3: Total Von-mises Stress (on pump housing) Averaged Max: 0.77822Mpa, Min: 1.207e-10Mpa
6.2 FOR 100N - GRAY CAST IRON

6.2.1. A) TOTAL DEFORMATION

![Total Deformation](image1)

**Figure 6.6:** Max: 0.00071624 mm, Min: 2.9154e-8 mm

6.2.1. B) DEFORMATION ON IMPELLER

![Deformation on Impeller](image2)

**Figure 6.7:** Max: 0.00033012 mm, Min: 2.641e-6 mm

6.1.2. B) EQUIVALENT STRESS ON IMPELLER

![Equivalent Stress](image3)

**Figure 6.4:** Unaveraged stress: Max: 0.99768 Mpa, Min: 6.036e-11 Mpa

**Figure 6.5:** Max: 0.11133 Mpa, Min: 1.207e-10 Mpa

**Figure 6.6:** Max: 0.00071624 mm, Min: 2.9154e-8 mm

**Figure 6.7:** Max: 0.00033012 mm, Min: 2.641e-6 mm

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http://ije-sc.org/
6.2.2. A) EQUIVALENT STRESS ON PUMP HOUSING

Figure 6.8: Max 0.78019 Mpa, Min 1.434e-10 Mpa

6.2.2. B) EQUIVALENT STRESS ON IMPELLER

Figure 6.9: Max 0.1108 Mpa, Min 1.4364e-10 Mpa

6.3 FOR POLYETHYLENE

6.3.1. A) TOTAL DEFORMATION

Figure 6.10: Max 0.065902 mm, Min 1.52e-6 mm

6.3.1. B) DEFORMATION ON IMPELER

Figure 6.11: Max 0.028372 mm, Min 4.9953e-5 mm

6.3.2. A) VON-MISES STRESS (TOTAL)

Figure 6.12: Max 0.77179 Mpa, Min 1.0672e-10 Mpa
6.3.2. B) VON-MISES STRESS ON IMPELLER

Figure 6.13: Max: 0.11616 Mpa Min: 1.0672e-10 Mpa

TABLE 6.1. Tabulated results for different load applications

<table>
<thead>
<tr>
<th>Serial NO.</th>
<th>Material Used</th>
<th>Pre-load</th>
<th>Equivalent Stress (Mpa)</th>
<th>Total Deformation (mm)</th>
<th>Deformation on Impeller (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Structural Steel</td>
<td>100N</td>
<td>0.77822 Max 1.207e-10min</td>
<td>0.00039015max 6.241e-9 min</td>
<td>0.00017839max 1.7028e-6 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500N</td>
<td>3.8911 Max 5.331e-10 Min</td>
<td>0.0019507 Max 3.1205e-8 Min</td>
<td>0.00089197 Max 8.5142e-6 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3500N</td>
<td>27.238 Max 3.5006e-9 Min</td>
<td>0.01365 Max 2.184e-7 Min</td>
<td>0.006243 Max 5.9599e-5 Min</td>
</tr>
<tr>
<td>2.</td>
<td>Gray cast Iron</td>
<td>100N</td>
<td>0.78019 Max 1.434e10 Min</td>
<td>0.0007162 Max 2.9154e-8 Min</td>
<td>0.0003301 Max 2.641e-6 Min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500N</td>
<td>3.901 Max 6.552e-10 Min</td>
<td>0.003581 Max 1.4577e-7 Min</td>
<td>0.0016506 Max 1.3207e-7 Min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3500N</td>
<td>27.307 Max 4.9541e-9 Min</td>
<td>0.02506 Max 1.020e-6 Min</td>
<td>0.011554 Max 9.244e-5 Min</td>
</tr>
<tr>
<td>3.</td>
<td>Polyethylene</td>
<td>100N</td>
<td>0.77179 Max 1.067e-10 Min</td>
<td>0.065902 Max 2.1532e-6 Min</td>
<td>0.028372 Max 4.995e-5 Min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500N</td>
<td>3.8589 Max 4.650e-10 Min</td>
<td>0.32951 Max 1.0766e-5 Min</td>
<td>1.14186 Max 0.00024977 Min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3500N</td>
<td>27.013 Max 4.2605e-9 Min</td>
<td>2.3066 Max 7.5136e-5 Min</td>
<td>0.99303 Max 0.0017484 Min</td>
</tr>
</tbody>
</table>

6.4 MODAL ANALYSIS OF CENTRIFUGAL PUMP IMPELLER

6.4.1 MODAL ANALYSIS OF STRUCTURAL STEEL IMPELLER

Figure 6.14: 1st mode shape

Figure 6.15: 4th mode shape
6.4.2 MODAL ANALYSIS OF POLYETHYLENE IMPELLER

6.4.3 MODAL ANALYSIS OF GREY CAST IRON IMPELLER
7. CONCLUSIONS

From the results, if we consider deformations, von-mises stresses on pump housing and impeller for full body. For three different material, structural steel, polyethylene and gray cast Iron for different loading conditions of 100N, 500N & 3500N.

<table>
<thead>
<tr>
<th>Load</th>
<th>Structural steel(MPa)</th>
<th>Gray cast-iron (Mpa)</th>
<th>Polyethylene (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100N</td>
<td>0.77822</td>
<td>0.778019</td>
<td>0.77179</td>
</tr>
<tr>
<td>500N</td>
<td>3.8911</td>
<td>3.901</td>
<td>3.858</td>
</tr>
<tr>
<td>3500N</td>
<td>27.238</td>
<td>27.307</td>
<td>27.013</td>
</tr>
</tbody>
</table>

If we consider yield strength criterion for linear Analysis.
- Allowable stress for structural steel will be - 250Mpa
- Allowable stress for polyethylene will be - 25 Mpa
- Allowable stress for gray cast Iron will be - 28 Mpa

From Results Critical load for structural steel, polyethylene and gray cast iron is 3500N. Also if we consider deformation for maximum load of 3500N

- Structural steel-total deformation-0.001365 mm
- Polyethylene-total deformation-2.3066 mm
- Gray cast Iron-total deformation-0.02506 mm

On doing static and modal analysis of pump impeller it is clear that, the maximum deflection induced in Impeller i.e. polyethylene material is 0.99303, which is in safe limits. The maximum induced stress for the same material is 27.103 Mpa which is less than the allowable stress i.e. yields strength .Hence the design is safe based on strength. If we compare corresponding deformation of the material polyethylene on above results with structural steel material and gray cast iron .Structural steel is having minimum deformation, therefore there are less chances of failure of the pump impeller as compare to other materials. Hence the strength of pump gets increased because of the Structural steel material. From the above result it is clear that weight of the Structural steel pump (13.782Kg) material is minimum as compared to cast Iron (14.5kg) material, hence weight of the pump fan reduced (optimized). The Natural Frequencies of structural steel is higher compared to gray cast iron and polyethylene, therefore structural steel has higher strength compared to cast iron and polyethylene. Structural steel is best material to suggest for Impeller design from this work.

8. REFERENCES


