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STRESS ANALYSIS OF VARIOUS DESIGNS OF CENTRIFUGAL PUMP IMPELLERS USING FINITE ELEMENT METHOD

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Abstract: The impeller blade is among the many critical components in a centrifugal pump that affect the efficiency of the pump, as it is the component through which the fluid passes. Therefore, the impeller requires as many analysis as possible to maximise its efficiency. The main requirement is to ensure that the impeller blade can withstand the level of stress thereby reducing the chance of blade fracture. In this paper, 4 different designs of a centrifugal pump impeller were analysed and compared using finite element analysis (FEA) under static analysis. The geometry of centrifugal pump impellers was modelled and analysed using Siemens NX™ software. This analysis provided an insight of performance of design where the blade's angle, width and shrouds are kept constant throughout the process. Calculations were performed to predict the design discharge and understand the impact on the impeller if the blade angle changes. The analysis revealed that the higher the outlet blade angle is to a point in comparison to the blade at inlet, the higher the head and the higher the pressure at the outlet will be. A pressure load of 1.866 MPa was applied evenly to the impellers with a rotation of 1,100 rpm and a torque of 29.187 Nm. Throughout the analysis, closed impeller blades were set to produce the least stress and displacement in comparison to other designs. Therefore, closed impeller was the best design, where the maximum stress was the lowest (86.09MPa) and can be more reliable in real life application.

Keywords: Centrifugal Pump Impeller; Optimisation; Finite Element Analysis; Stress Analysis.

1. Introduction

Pumps is a typical fluid machine that is widely used in various industries (Babalola et al, 2019). The impeller converts mechanical energy into fluid pressure and kinetic energy. The most common types of pumps are the centrifugal pump which have been used in industrial fields, such as water, drainage, sewage, and chemical industry. As a result, much research has been accomplished on various design of centrifugal pumps (Kim et al, 2012). The basic types of pumps are divided into two types: positive displacement and dynamic pumps. Typical examples of positive displacement pumps are plungers and pistons. Types of dynamic pumps include mixed, axial, and radial flow which are known as centrifugal pumps.

This paper focuses primarily on radial centrifugal pumps (Babalola et al, 2019). The impeller is the central component, and it transforms the mechanical energy into pressure energy that directly defines a centrifugal pump's transport power and hydraulic performances. Optimised impeller design is important and substantial for a centrifugal pump to work efficiently (Matlakala et al, 2019). Therefore, the impeller requires the most analysis possible to maximise its efficiency. Reducing the level of stress subsequently minimising the chance of blade's deformation or fracture is the main purpose of the any proposed design. By enabling the pump's impeller to withstand a higher amount of stress and obtaining the least amount of distortion, the expense of buying an additional impeller can be reduced. Most significantly, impeller manufacturing would be reduced, ensuring that less energy is needed to manufacture the part which results in a more environmentally friendly product.

A centrifugal pump is a mechanical device designed to transfer fluid from one or more driven rotors, named impellers, through the transfer of rotational energy. Impellers are the most critical parts of centrifugal pumps. Impellers include a variety of curved vanes (Michael-smith-engineers, 2020). Typically, there are three forms of impellers: open, enclosed, and semi-open (Kim et al, 2012). The volute, shaft, and impeller are the main pump components of a centrifugal pump. The impeller is connected to a shaft. The basic purpose of a centrifugal pump shaft is to support the impeller and other rotating parts while transmitting the torque encountered during start-up and operation. The work must be done with a deflection lower than the minimum clearance between turning and fixed components (Bachche & Tayade, 2013).

Each impeller has one or several vanes from the core or centre to the outer diameter of the impeller. As the impeller spins, centrifugal force allows the fluid to rapidly move into the core of the impeller, across the vanes, and then leaves the impeller on the furthest outer diameter. As a result, the propelled fluid exits the impeller's edge at an extremely high rate and directly into the volute's inner casing wall (Michael-smith-engineers, 2020). Centrifugal pumps are often needed to provide enough energy to supply the fluid to the pump suction nozzle. It is not necessary for centrifugal pumps to draw the liquid into the pump frame. The mechanical power is the input for the centrifugal pump, and the output is hydraulic energy. Therefore, a centrifugal pump is a tool that converts mechanical energy to hydraulic energy to bring water to a necessary position (Khaing et al, 2019). Currently, the research on centrifugal pump design is focused on computational fluid dynamics (CFD) analysis, and structural analysis is rather limited.

Therefore, the aim of this paper was to analyse and compare different designs of a centrifugal pump impeller using finite element analysis (FEA) under static analysis. The geometry of centrifugal pump impellers is modelled and analysed using Siemens NX™ software. This analysis helps us to gather information including stress and displacement so that they can be easily compared to find the best design.

2. Material and Methods

The design process of the impeller is highlighted in **Figure 1**. Four designs have been carried out and demonstrated in this study. First design shown in **Figure 1**(a) is an open impeller where the impeller has no shrouds to direct the flow of liquid. The diameter of the open impeller is 270 mm from one tip of the blade to the other. There are 6 blades with a maintained thickness of 11 mm. and the height of the blade is 40 mm.

The second design was a semi-open impeller shown in **Figure 1**(b) where a shroud exist to direct the liquid between the veins. The shroud has a thickness of 25mm and a diameter of 270 mm. The design of the impeller blades remained approximately the same so that the designs could be appropriately compared when performing the analysis.

Then a modified semi-open impeller introduced and shown in **Figure 1**(c) with a shroud. In this design the blades are shortened, and the eye of the impeller is edge blended to see if this affects the stress distribution on the impeller. The inner eye diameter where the shaft is placed is set to be 30 mm.

The final design shown in **Figure 1**(d) is a closed impeller. In this design the vanes are enclosed by shrouds on both sides. The shroud guides the flow of liquid between the blades. Closed impellers are often used for low viscosity or thin liquids. Thick or suspended solids can clog closed impellers. For these types of liquids, open impellers can be used.

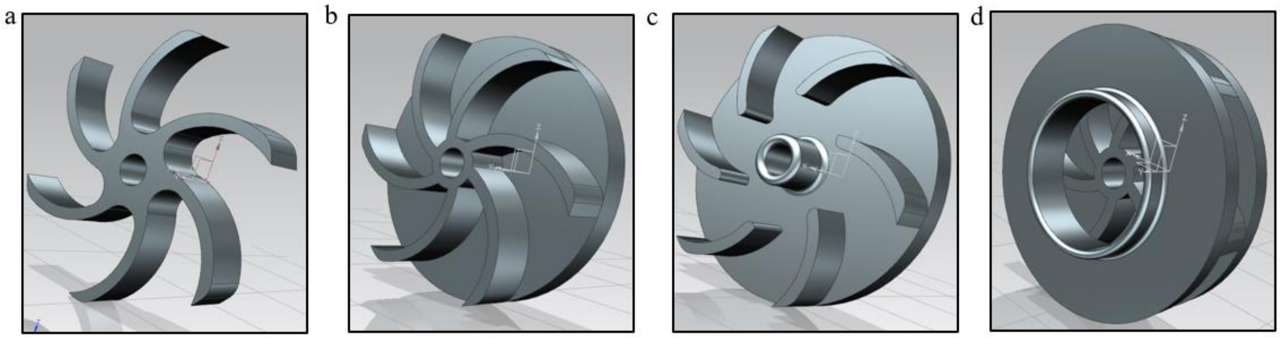

Figure 1. (a) Open impeller (b) Semi-open impeller (c) Modified Semi-open impeller (d) Closed impeller.

2.1 Finite Element Procedures

Finite element analysis is a computer-based numerical method used to calculate the strength and performance of a model design. This can be used to calculate buckling behaviour, stress, deflection and many other occurrences (Prasad et al, 2013). In order to perform a finite element analysis, the design used must be split into many small sections called finite elements. Because the design is split into multiple separate sections, FEA can be described as a discretization technique. In short, a mathematical mesh or net is needed for finite element analysis (Selamat et al, 2018).

2.2 Static Analysis

Linear static analysis, solution 101, uses global constrains to run the analysis for the centrifugal pump impellers. Static analysis calculates the impacts of steady-state load conditions on the design, while disregarding damping and inertia effects, such as those caused by time-dependent loads. Static analysis is used to identify stresses, strains, displacements and forces in structures and components induced by loads that do not produce major damping and inertia effects (Traya & Rathod, 2020). However, static analysis may include stable inertial loads (including gravity, acceleration and angular velocity), as well as loads that change over time. These loads can be computed as static equivalent loads (Structures aero, 2019).

2.3 Meshing

Meshing is required to start the simulation for the centrifugal pump impellers. With meshing, a domain is divided into sections, each section represents an element. By increasing the number of elements, more computations would be produced and therefore, more mathematical formula on that element. The finer the mesh, the more precise the results would be. In this analysis, a 3D tetrahedral mesh is used with an element size of 3 mm. Also, the material assigned is steel with a yield strength of 137.895 MPa at room temperature.

2.4 Loads and Constraints

A fixed translation constraint is applied at the centre of the impeller eye. This applies a constraint where all translational degrees of freedom are fixed and all rotational are free. A pressure load of 1.866 MPa is applied evenly to the impellers as shown in **Figure 2**(a). The fixed translation constraints can also be seen at the **Figure 2** where the impeller eye is located. A rotation of 1,100 rpm is applied with a torque of 29.187 Nm at the impeller eye where the shaft is placed. Back curved vanes help to stabilize flow conditions at high speeds and reduce demands on the motor. Therefore, the correct direction of rotation for these impellers is counter-clockwise. By looking at the way that vanes are curved, it’s easy to predict the correct direction of rotation of an impeller.

The solution can then be solved, and the structural results can be displaced. The results of displacements and Von Mises stress can then be analysed. This process is repeated for all impeller designs.

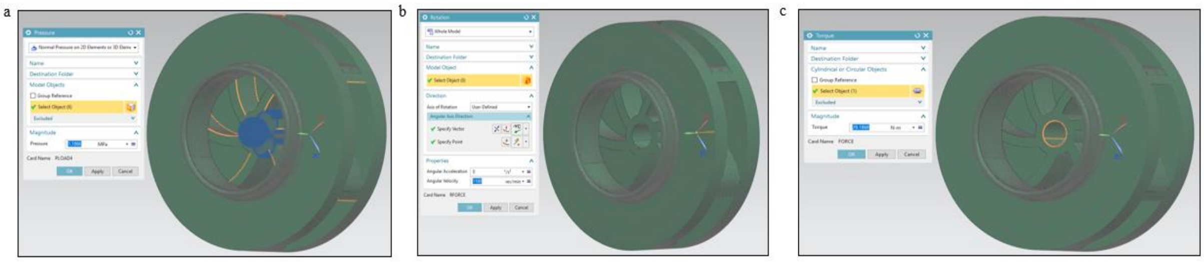

Figure 2. (a) 1.86 MPa pressure at the impellers (b) 1100 rpm rotation (c) 29.187 N.m. torque.

2.5 Von Mises Stress

Von mises stress or similar tensile stress can be expressed as the von Mises yield criterion in material science and engineering. Von Mises stress is used to anticipate the yield of a material in any load condition based on the results of a basic uniaxial tensile test, as when the material's von Mises stress achieves a significant value called yield strength, the material starts to yield (Prasad et al, 2013).

3. Results and Discussion

The aim of the static analysis was to understand the response of the impeller blades under pressure. From the calculations, at an angular velocity of 1,100 rpm, the pressure was generated on the impeller is 1.186 MPa and the torque is 29.86 Nm. The analysis helps to identify the amount of stress and displacement induced and where it is being generated, due to the load distribution and fixed translation from the hub. As the impeller rotates, it can be seen from the results that the maximum displacement of 1.00mm (see **Figure 3**(b)) occurs at the exit of the impeller blades than the rest of the part. Refer to **Figure 3** at the high displacement region, the corresponding stress is relatively low. This suggests that high deflected region tends to be less resisting the external load, and so the corresponding stress value is relatively low.

3.1 Open Impeller

Figure 3 produced a maximum and minimum stress (Von Mises) of 340.49 MPa and 1.18 MPa and a maximum displacement of 1 mm in open impeller. The highest stress is established at the inner blade next to the hub. The yield point of a material in engineering and materials science is the stress at which the material starts to deform. Before the yield point, the material will elastically deform and restore its original shape after removing the applied stress. Once the yield point passes, some parts of the deformation will be permanent and irreversible (Babalola et al, 2019). The maximum yield strength of the assigned material steel is 137.895 MPa. Therefore, the analysis result of the open impeller design has significantly surpassed its yield point, and the design is set to fail.

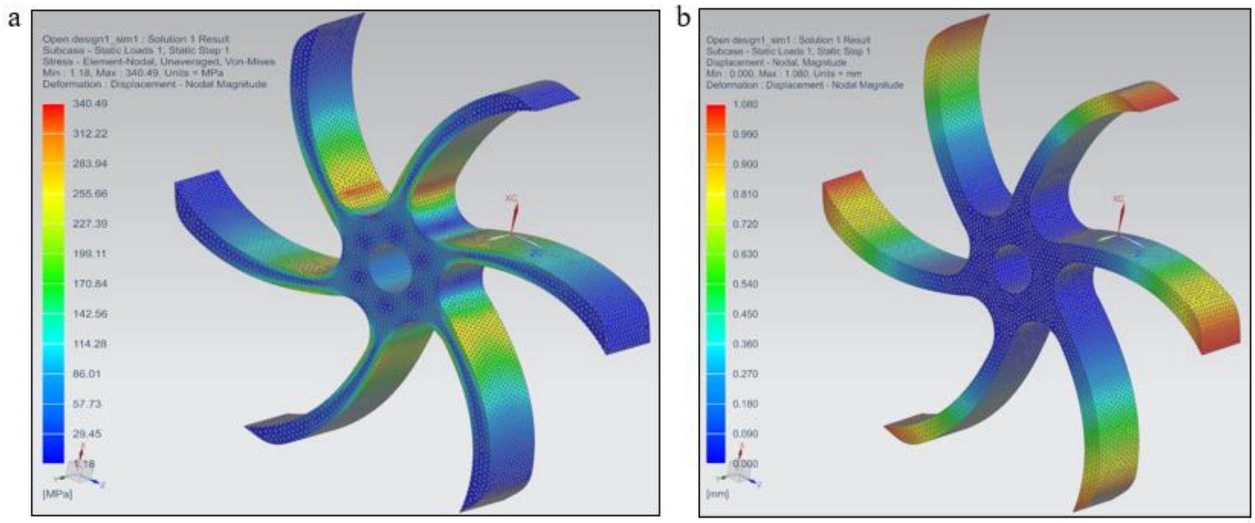

Figure 3. Open impeller (a) Stress-element-nodal, Von Mises (b) Displacement-nodal, magnitude.

3.2 Semi-Open Impeller

Figure 4 shows the analysis result of a semi-open impeller. The model consists of a shroud to direct the liquid between the veins. It can be seen that the model would withstand much greater stress in comparison to the open impeller. The model design produced a maximum and minimum stress (Von Mises) of 145.82 MPa and 0.15 MPa and a maximum displacement of 0.0654 mm. The stress figure looks comparatively blue indicating that the stresses are less than 145.82 MPa. The semi-open impeller design has also surpassed its yield point, and the design is set to fail.

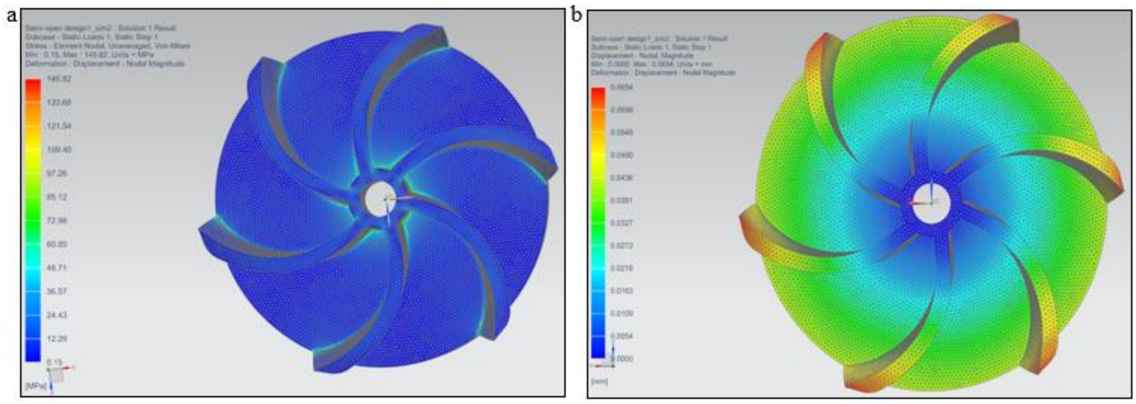

Figure 4. Semi-open impeller (a) Stress-element-nodal, Von-Mises (b) Displacement-nodal, magnitude.

3.3 Modified Semi-Open Impeller

Figure 5 shows the analysis result of a modified semi-open impeller with a shroud to direct the liquid between the veins. In this design the blades are shortened, and the eye of the impeller is edge blended. It can be seen that the stress is more distributed at the impeller eye in comparison to the semi-open impeller design at **Figure 4** resulting in a lower stress at that region. However, due to the shortening of the blades, there is less support, therefore there is a lot more stress. The modified semi-open impeller at **Figure 5** produced a maximum and minimum stress (Von Mises) of 157.92 MPa and 0.03 MPa and a maximum displacement of 0.0654 mm. Although they produced the same amount of displacement, the stress of the modified design is much higher than the semi-open impeller design at **Figure 4**. Therefore, if the impeller produced the same amount of water discharge, the semi-open impeller is set to be the better design as it produced less stress. Nevertheless, in both cases, the design has surpassed its yield point, and the design is set to fail.

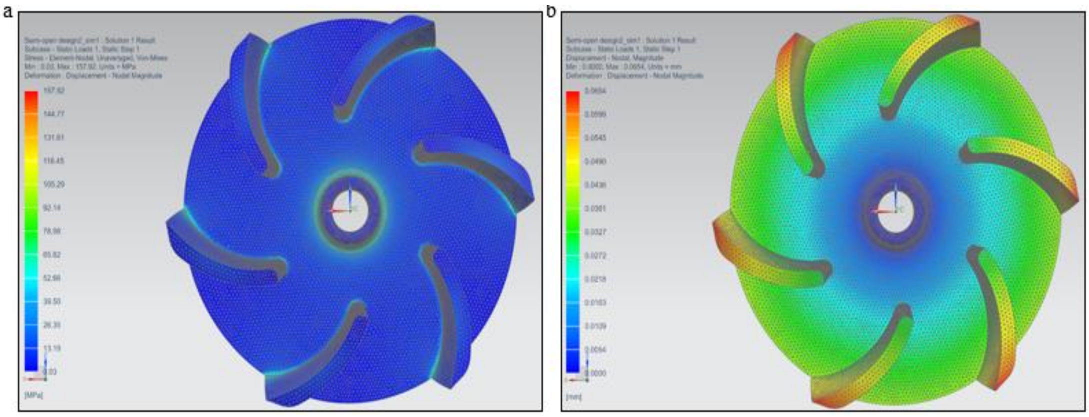

Figure 5. Modified Semi-open impeller (a) Stress-Element-Nodal, Von-Mises (b) Displacement-Nodal, Magnitude.

3.4 Closed Impeller

Finally, **Figure 6** shows the analysis result of a closed impeller. Its vanes are enclosed by shrouds on both sides to guide the flow of liquid between the blades. The model produced the least maximum and minimum stress (Von Mises) of 86.09 MPa and 0 MPa and the least maximum displacement of 0.0434 mm. The analysis figure indicates that the displacement is higher at the other side of the shroud than the one connected to the shaft as there is less stress at that shroud in comparison to the one connected to the shaft. This is because the highest stress is established at the impeller eye where the shaft is located. This is where the maximum movement occurs as the maximum stress is distributed at this point and this would be the first point where the model would begin to fail. The maximum yield strength of the assigned material steel is 137.895 MPa. Therefore, the analysis result of the closed impeller design did not surpass its yield point, and the design is set to be safe.

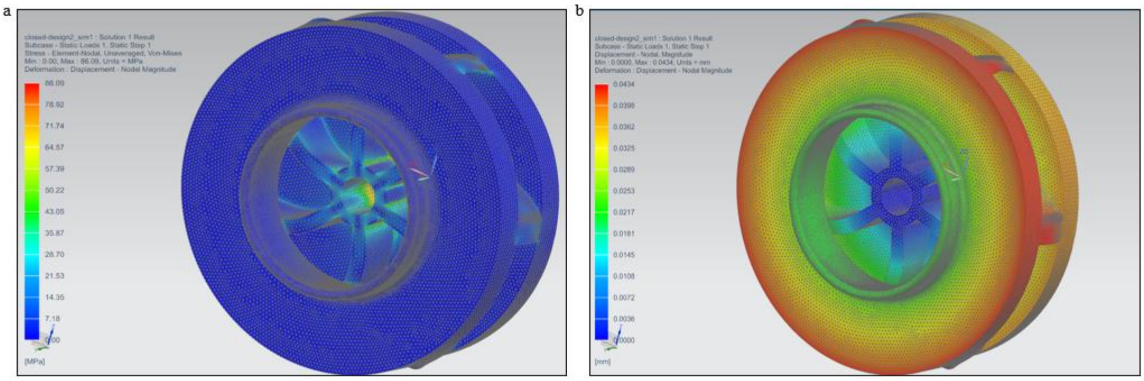

Figure 6. Closed impeller (a) Stress-element-nodal, Von Mises (b) Displacement-nodal, magnitude.

4. Conclusion

The main aim of this study was to investigate different design of the impeller to achieve best performance in terms of withstanding loads and stresses. For this aim four designs including open, semi-open, modified semi-open and closed impellers have been modelled and FEA analysis has been caried out. Comparing all stress and displacement produced by running the FEA analysis, it’s clear that the closed impeller design is the best design, where the maximum stress and displacement are the lower. The design supports the impeller blades and relieve stress on the model. The maximum stress and displacement value generated by the closed impeller design is 86.09 MPa and 0.0434 mm, followed by semi-open and modified impellers with maximum displacement of 0.0654 mm for both and maximum stress of 145.82 MPa and 157.92 MPa respectively. The last design which is open impeller is generated maximum vin mises stress of 340.49 and maximum displacement of 1 mm, which indicate the least efficient design. Although the results shown that the closed impellers are more reliable than other three proposed designs, however further analysis should be carried out in order to see which design is more efficient, as it has been assumed that the impeller design produces the same amount of water discharge. To conclude from the analysis of the four models, the closed impeller design is the most efficient design as the analysis result of the closed impeller design did not surpass its yield point, and it is the only design that is set to be safe. While the other designs have significantly surpassed their yield points, the designs are set to deform permanently and fail.

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