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Research Paper / *Araştırma Makalesi*

Comparative Static and Frequency Case Analysis of Water Pump Impeller: A Case Study for Brass, Aluminium, Titanium and Plastic Material

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ABSTRACT
This study addresses the modeling and static case analysis of carbon steel and alloy steel water pump impeller to inspect the deformation, stress, strain, vibrations and displacement. Pump impellers are mostly manufactured with stainless steel or mild steel in which its relative high density has led to an increase in corrosion resistance, weight and a low tensile strength. A brass, aluminium, titanium or plastic material can be deployed instead of carbon steel to enhance decomposition, durability and to create a lightweight pump impeller. For each of the material, the part geometry of the pump impeller and modeling is done separately using CATIA V5R20. Using FEM, the mesh visualization was done separately and in order to monitor the stress and deformation behavior, a force of 500N was used to make the von Mises stress values more significant and also to satisfy the static case. The applied force is being used to compute and display the von-misses stress, displacements, and deformation. The primary goal of this paper is to investigate for the most favorable material that is best suitable for manufacturing impeller. A structural analysis has been carried out to investigate for the best stress value between the materials as well as its displacement. This study also explains the modal analysis in demonstrating how quick either of the materials gets deformed with respect to its natural frequencies.

Keywords: *Finite element method, generative structural analysis, impeller, static analysis, water pump*

INTRODUCTION

Water pumps are commonly used on construction sites for dewatering or removing excess water accumulation. Water can build up due to heavy rains or from a high water table and pumps allow it to move the water quickly to minimize downtime. Water pumps suitable for this application come in two main types and can be electric, gas-powered, hydraulic or manual. A centrifugal water pump uses a rotating impeller to move water into the pump and pressurize the discharge flow. Centrifugal pump has its applications in oil refineries, food processing factories, sewage, irrigation, hydraulic power service, mines, steam power plants and chemical plants (Khin et al., 2008).

An impeller is a rotating part of a centrifugal pump, mostly made up of metal or non-metal transferring energy from the motor that drives the pump to the fluid being pumped by accelerating the fluid outwards from the center of rotation (Anirudha and Gore, 2017).

Water pump impellers are mostly manufactured with stainless steel or mild steel in which its relative high density has led to an increase in corrosion resistance, weight and a low tensile strength. This stainless steel or mild steel can be replaced with other materials (e.g. brass, titanium, aluminium, bright plastic) to improve corrosion resistance, reduce the weight and increase the tensile strength. Brass, titanium, aluminium and bright plastic are the chosen materials to be used as a case study in this paper to determine the material with the minimum deformation, highest strength and natural frequencies.

The materials selected to be used have been chosen as a result of the following reasons;

1. **Aluminium:** It is a non-ferrous metal, very lightweight, approximately one third as much as steel. It exhibits excellent atmospheric corrosion resistance.
2. **Brass:** It comes with good strength and has good bearing properties, low magnetic permeability, excellent

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high temperature ductility and reasonable cold ductility.
3. **Titanium:** It has an excellent strength-to-thickness ratio.
4. **Bright plastic:** It provides broad chemical resistance and is less costly and lighter in weight than metal.

Impellers can be further classified principally into three subtypes; Propeller, paddler and turbines. In this paper, semi open impeller type of the centrifugal pump is taken into consideration for the design. Sampathkumar et al. (2014) studies on the choice of E-glass (composite material) as an alternative to Aluminium for efficient vibration control of a centrifugal blower shows that E-Glass blower is more suitable compared to Aluminium due to the fact that the stress value of the E-Glass blower shown in the static analysis lies within the allowable stress limits with a less weight of 15kg as to the Aluminium weight of 19kg. Pandya and Patel (2014) assessed on the CFD analysis of centrifugal pump impeller reveals that through the usage of empirical relations, the velocity and pressure of the impeller outlet can be deploy as a tool in calculating for the efficiency of the existing impeller.

Ghanshyam and Gandigude (2017) studies on the structural analysis and material optimization of centrifugal pump impeller using finite element analysis shows that stresses are higher at the shaft location with all the materials having a lower stress values as compared to their permissible stress values. It was reported during the comparison between finite element analysis and experimental testing that glass fiber is the most preferred alternative material due to its non-corrosive properties, less weight and good strength.

Anirudha and Gore (2017) describes finite element analysis as one of such numerical procedure for analyzing and solving wide range of complex engineering problems (may be structural, heat conduction, flow field) which are complicated to be solved satisfactorily by any of the available classical analytical methods.

Rajendran and Puroshothaman (2012) performed an analysis of a centrifugal pump impeller using ANSYS-CFX to create a turbulent model and to predict the internal flow of the centrifugal pump impeller. The types of material used in manufacturing impeller go a long way in determining its durability, strength and efficiency. Syam *et al*. (2013) has carried out a computational analysis on a centrifugal pump impeller in which Inconel alloy 740, Incoloy alloy 803 and Warpaloy were used as materials. They observed that the best suggested material for the design of impeller is inconel alloy 740. Sajjan *et al*. (2016) has also carried out a computational analysis on impeller type centrifugal pump and realize that the natural frequencies and strength of structural steel is higher compared to cast iron and polyethylene. They suggested from their work that the best material for impeller design is structural steel.

MATERIALS AND METHODS

The stages involved in this research work are 3D Modeling of the impeller using CATIA V5 R20, meshing visualization using CATIA V5 R20, creating a distributed force load, computing a static case solution (static analysis simply refer to the means of analyzing the static boundary conditions of the CATAnalysis document), viewing displacement, Von-Mises stress, and deformation results, and computing the frequency case solution (analyzing the dynamic boundary conditions of the CATAnalysis document) to view the frequency results.

3D Modeling of the Impeller Using CATIA V5 R20

Using part design of the mechanical design module of CATIA, a helical profile was used in creating a xy plane surface with a circle of 80mm, pad (Extrusion height) of 8m. Using helix curve definition at the wireframe surface design, parameters such as Axis (Z), pitch (250mm), Tape angle (10), Revolution (1), height (30), Orientation (Counterclockwise), and way (Inward) must be defined. Clicking the surface of the small cylinder, a coincidence operation must be performed in contact with the edge of the small cylinder. The same process is repeated (just that the surface if the bottom was clicked in this case). Lines are then created to connect the two lines after which the multi section solid was applied in connecting all of the lines. The thickness function in the part design is then used in transforming the surface into a solid. To pattern the solid from the thickness, the circular pattern definition was used. The type of parameters (complete crown), number of instances (8), reference element (circular cylinder surface) and the thick surface of the object must be chosen to create the circular pattern. The solid model of the water pump impeller is shown in shown below in Figure 1.

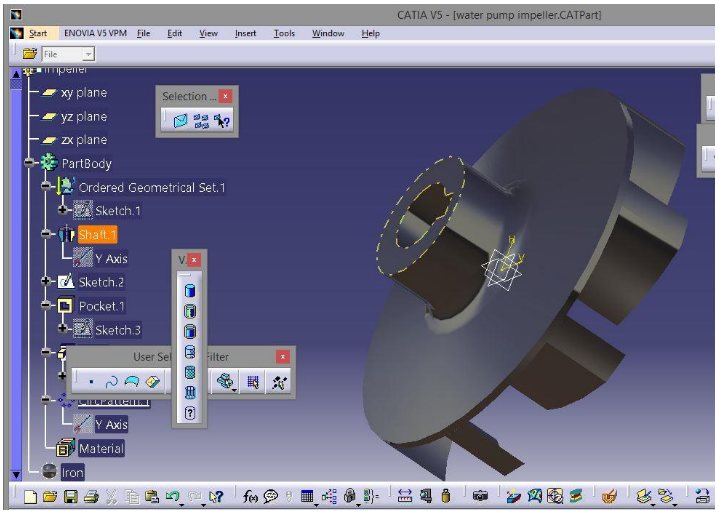


Figure 1. Solid model of the water pump impeller

Meshing Visualization Using CATIA V5 R20

After the solid model of the water pump impeller, the meshing visualization is achieved by selecting Start > Analysis and Simulation > Generative Structural Analysis workbench. Once the New Analysis Case box appears, the Static Analysis is selected while we also click on the OK. The mesh is seen by right clicking on Nodes and Elements in the design tree and click Mesh Visualization. For better visualization, the mesh parts, the Properties.1 set, Restraints.1 set and the Loads.2 set can be hidden one by one by right clicking the entity needed to be hidden in the specification tree and finally selecting show/hide. The meshed model is shown in Figure 2.

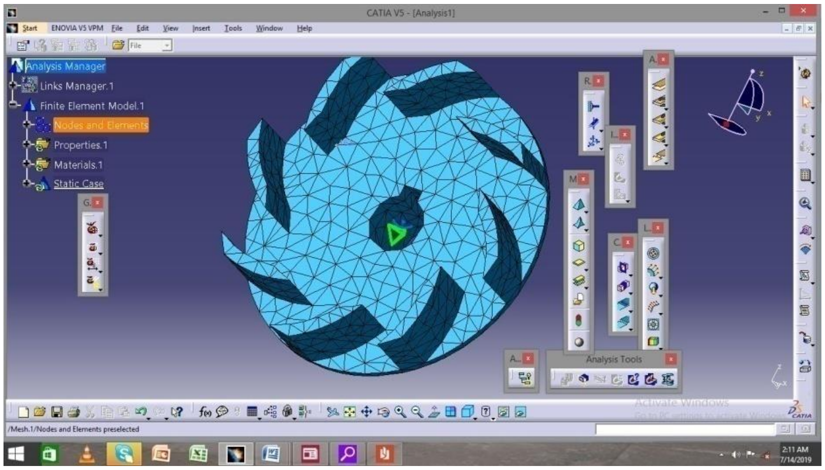


Figure 2. Meshed model of the impeller using CATIA V5 R20

Creating a Distributed Force Load

A surface restraint was created on a finite element model containing a static analysis case by selecting the Restraints.1 object in the specification tree to make it active and then clicking the surface slider icon (the surface dialog box appears immediately) which gives access to select the faces of the impeller blade. This will be achieved by distributing a resultant force of 500N parallel to the global z-direction on the faces of the impeller blades. 500N distributed force (load) was used in order to make the Von-Mises stress values more significant and also to satisfy the static case. Entering -500N value in Z field (Force vector) will automatically update the resultant force vector norm and make the Distributed Force.1 object inserted under the Loads.1 objects set in the specification tree.

Computing a Static Case Solution

The static case solution must be computed with the already available Restraint object and Load object. This task was carried out by selecting storage location icon in the CATIA software and then selecting the compute icon (compute dialog box appears). In the compute dialog box, the all default value is selected to launch the computation by clicking on Ok. During the process of computation, the progress bar display series of status messages such as Meshing, stiffness computation, constraint computation, factorization etc. that helps to know the degree of advancement of the computation process. The completed computation will then prompt the status of all objects (at the analysis specification tree and the static case solution.1 objects set) to be changed to valid (with the Restraint and Load symbol turning to blue which signifies that the static case solution was successfully computed)

Viewing the Results for Von-Mises Stress, Displacements and Deformation

The results for the Von-Mises stress, displacements and deformation can be viewed after successful computation of the static case solution by clicking on their respective icon in the CATIA software with the material option being active. Clicking on the Von Mises stress icon will display the nodal values of the Von-Mises stress. To obtain the global extrema values of the Von-Mises stress field magnitude, the search image extrema icon can be clicked alongside defining the two absolute extrema needed. Clicking on the displacement icon will display a plot of the displacement field with arrow symbols. The nodes can then be visualized when the cursor is moved over the plot.

Computing a Frequency Case Solution

The materials option must be activated or selected from the material library before inserting a frequency case from the menu bar of the generative structural analysis of the CATIA software. Once the frequency case with a new feature has been created, the new analysis solution and its structure of analysis specification tree will be shown. To compute the frequency case solution, the storage icon and compute icon will be clicked to choose the all default and finally clicking Ok to perform the computation. The status of the frequency case solution becomes valid at the specification tree after the computation is completed. Clicking the deformation icon helps to visualize the frequency at which the impeller get deformed after computing the analysis case. An image of the deformed impeller corresponding to the frequency mode is displayed and immediately the deformed mesh image object will appear at the specification tree. To display the list of vibration modes with the corresponding frequency occurrences, the deformed mesh object must be double clicked under the specification tree. Any mode selected in the frequency list will display the deformed shape of the impeller at its own level.

Table 1. Material properties

Material Selected	Young Modulus	Density	Poisson Ratio	Yield Strength
Aluminium	7E+010N/m^2	2710kg/m^3	0.346	9.5E+007N/m^2
Brass	1.31E+011N/m^2	8216kg/m^3	0.35	3.5E+008N/m^2
Titanium	1.14E+011N/m^2	4460kg/m^3	0.34	8.25E+008N/m^2
Bright Plastic	2.2E+009N/m^2	1200kg/m^3	0.38	0N/m^2

FINDINGS

For 500N Aluminum Material

Using aluminium material with a distributed force (load) of 500N, the value obtained for the Von-Mises stress as shown in Figure 3 is 1.06e008 (Global max.) which shows that the water pump impeller will undergo failure if the aluminium material is being used since its Von Mises stress value exceeds the value of the yield strength (9.5E+007N/m^2) shown in Table 1.

Aluminium being a ductile material (homogenous) will result to formation of fatigue cracks that is due to accumulation of irreversible plastic deformation. Using aluminium, it can be seen that the impeller as shown in Figure 4 get deformed quickly before undergoing fracture due to its high value (shown in Table 2). For small values of strain during elastic deformation, the strain experienced by the impeller will be linearly related to the stress applied on it.

As shown in Figure 6, the frequencies of the impeller at different modes of the 500N aluminium material are smaller in value which implies a reduction in the strength since a higher value of frequency at different level of modes will give rise to an increase in strength of the impeller.

The translational displacement value of the impeller (considering the aluminium material) is smaller which implies a slight decrease in the rate at which the impeller blade will change position.

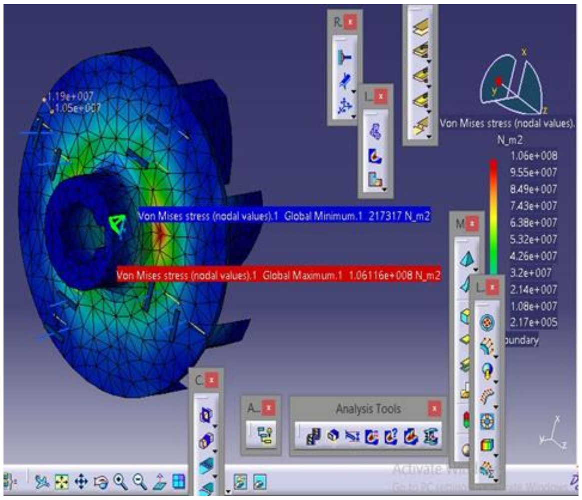


Figure 3. Von-mises stress of water pump impeller

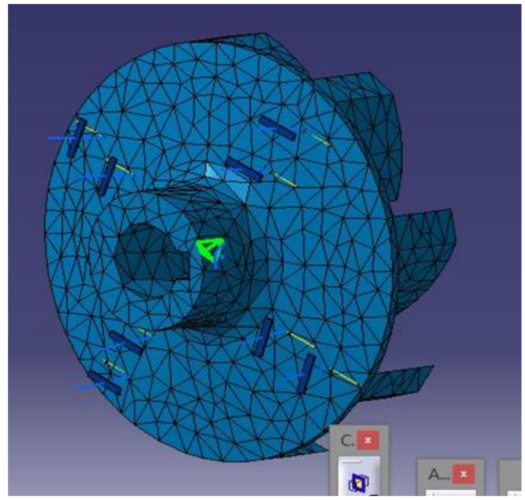


Figure 4. Deformation of water pump impeller

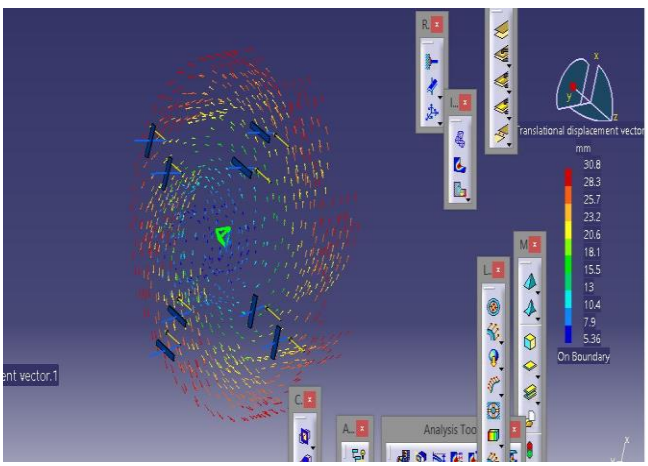
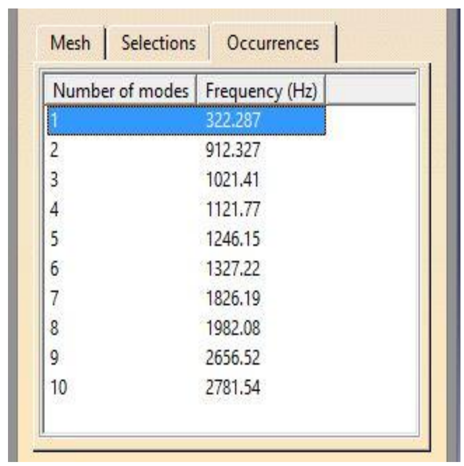


Figure 5. Translational displacement vector of the impeller (aluminium)



Mesh | Selections | Occurrences

Number of modes	Frequency (Hz)
1	322.287
2	912.327
3	1021.41
4	1121.77
5	1246.15
6	1327.22
7	1826.19
8	1982.08
9	2656.52
10	2781.54

Figure 6. Impeller Freq. at different modes

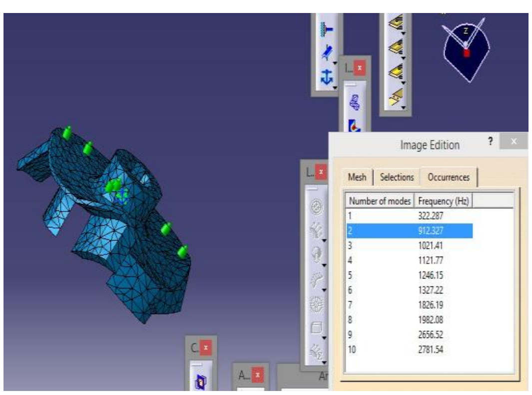


Figure 7. Shape of the 2nd mode

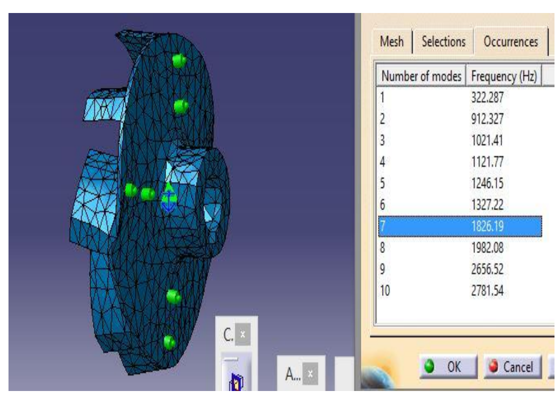


Figure 8. Shape of the 7th mode

For 500N Brass Material

Using Brass material with a distributed force (load) of 500N, the value obtained for the Von-Mises stress as shown in Figure 9 is 9.66e007 (Global max) which shows that the water pump impeller is efficient enough with no likelihood of undergoing any failure if the brass material is being used since its Von-Mises stress value do not exceed the value of the yield strength (3.5E+008N/m^2) shown in Table 1.

Table 2 shows that Brass has the lowest value in terms of deformation which implies that the rate at which the impeller will change shapes is extremely low (as shown in Figure 11) when compared to aluminium, titanium and bright plastic.

The translational displacement value (as shown in Figure 10 and Table 2) of the impeller (brass material) is smaller which also implies a slight decrease in the rate at which the impeller blade will change position.

Figure 12 shows that the frequency of the impeller at different levels of the mode for 500N Brass material is of higher values which implies higher strength of the impeller. This will enable the impeller to withstand the applied load without any failure.

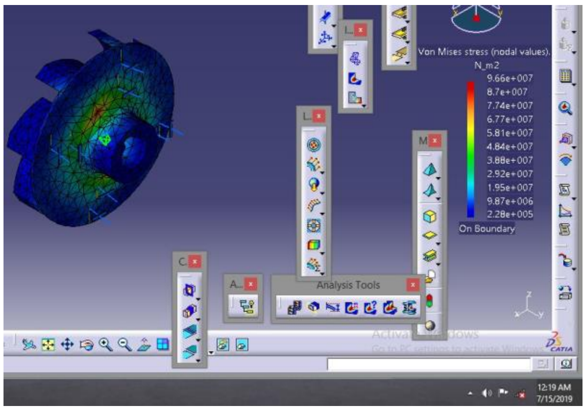


Figure 9. Von-Mises stress of water pump impeller

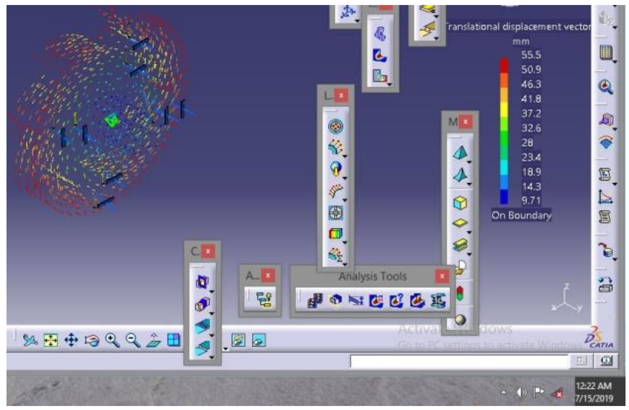


Figure 10. Translational displacement (brass)

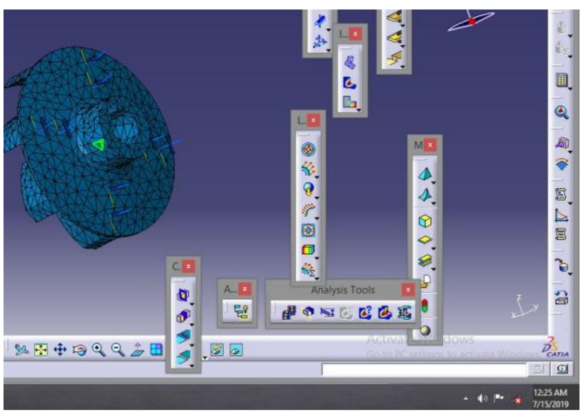


Figure 11. Deformation of water pump impeller

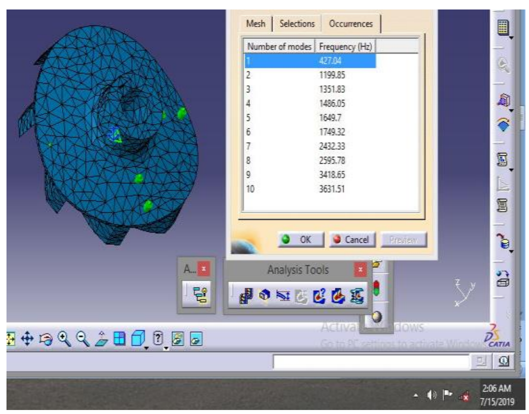


Figure 12. Freq of the impeller at different modes

For 500N Titanium Material

Using titanium material with a distributed force (load) of 500N, the value obtained for the Von-Mises stress as shown in Figure 13 is 9.78e007 (Global max.) which also shows that the water pump impeller is not expected to undergo failure if the titanium material is being used since its Von-Mises stress value do not exceed the value of the yield strength (8.25E+008N/m^2) shown in Table 1.

Figure 16 shows that the frequency of the impeller at different levels of the mode for 500N Titanium material is also of higher values (but not more than brass material) which implies higher strength of the impeller. This also will enable the impeller to withstand the applied load but likely to undergo failure due to its high value of deformation which is much more than that of aluminium and brass material despite its (titanium) lower value of displacement.

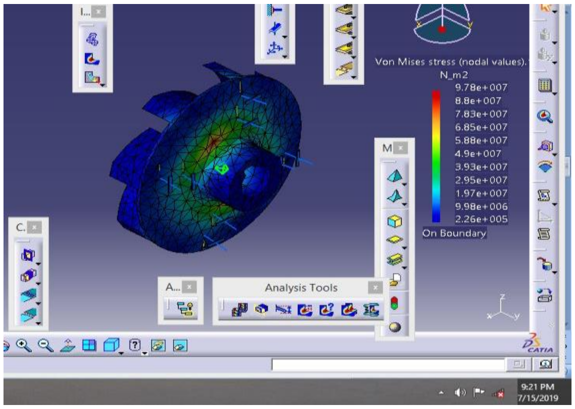


Figure 13. Von-mises stress of the impeller

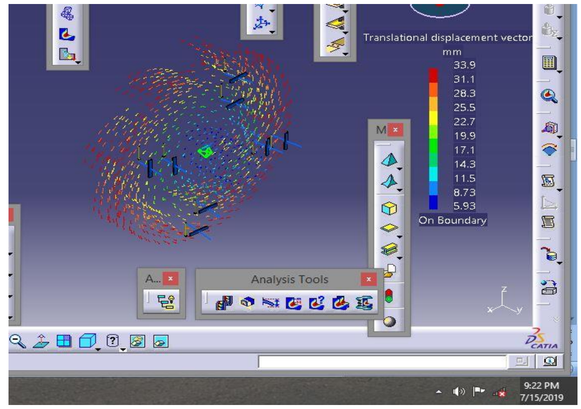


Figure 14. Translational displacement (Titanium)

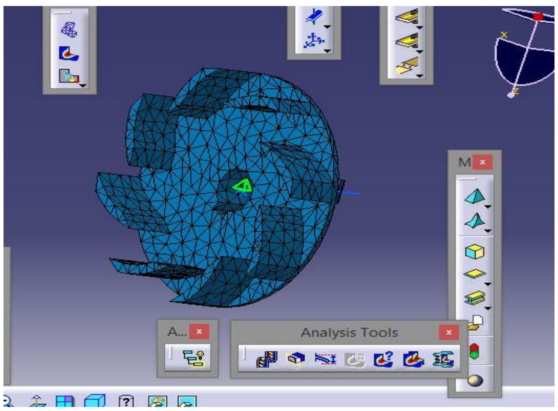
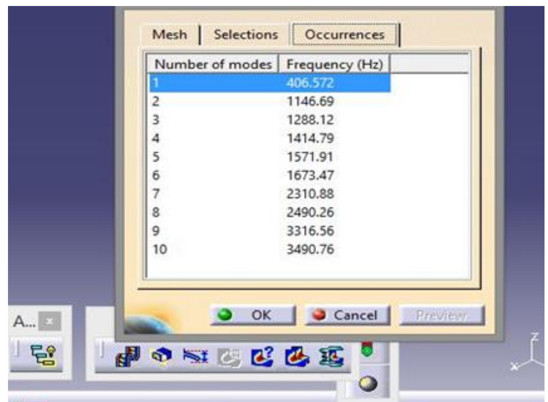


Figure 15. Deformation of impeller



Number of modes	Frequency (Hz)
1	406.572
2	1146.69
3	1288.12
4	1414.79
5	1571.91
6	1673.47
7	2310.88
8	2490.26
9	3316.56
10	3490.76

Figure 16. Frequency at different modes

For 500N Bright Plastic Material

Using bright plastic material with a distributed force (load) of 500N, the value obtained for the Von-Mises stress as shown in Figure 17 is 8.94e007 (Global maximum) which shows that the water pump impeller will undergo extreme failure if the Bright plastic material is being used since its Von-Mises stress value exceeds the value of the yield strength (0N/m^2) shown in Table 1.

Considering the translational displacement value obtained when a force of 500N was used, it can be deduced that its high value (as shown in 18) will result to changes in the point of the impeller blades and in turn give rise to deformation.

Deformation occurs in plastic when subjected to compressive, bending, tensile or torsion stress that exceed its yield strength and cause it to compress, bend or elongate. Under stress, deformation in plastic comprises of strain hardening region (material becomes stronger), necking region (material no longer able to withstand the maximum stress) and finally a fracture. The deformation of the impeller (plastic material) is shown in Figure 19. The high value (0.850) of deformation (shown in Table 2), in addition to the smaller values of natural frequency at different modes (Shown in Figure 20) for the plastic material implies that the material type is extremely low in terms of strength with chances of failure being high.

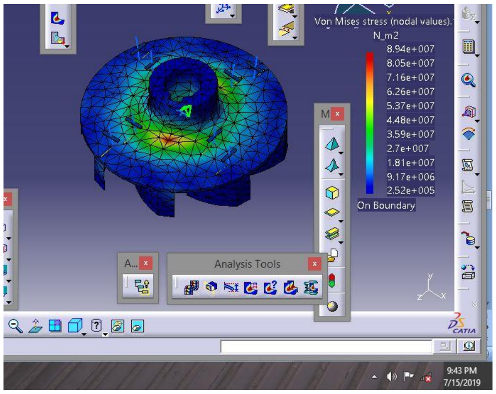


Figure 17. Von-Mises stress of the impeller (bright plastic)

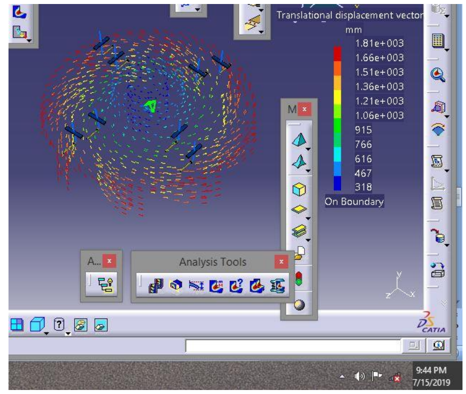


Figure 18. Translational displacement stress

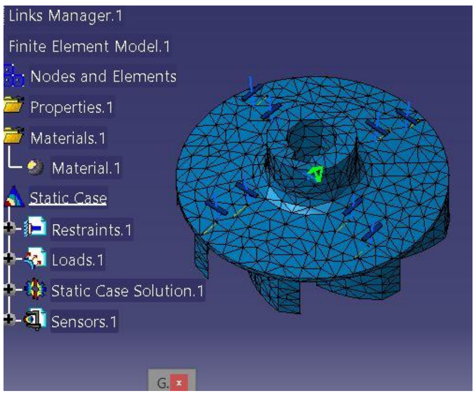


Figure 19. Deformation of the impeller

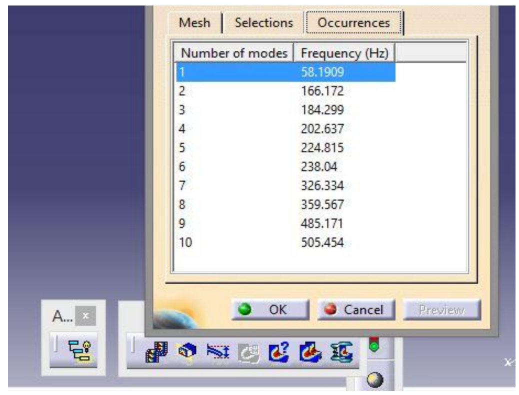


Figure 20. Frequency at different modes

Table 2. Static analyses of the materials

Properties	Aluminium	Brass	Titanium	Bright Plastic
Von-Mises Stress (MPa)	106	96.6	97.8	89.4
Deformation (mm)	0.0235	0.0215	0.0242	0.850
Displacement (mm)	0.0308	0.0555	0.0339	1.81
Load	500N	500N	500N	500N

Table 3. Natural frequencies of the materials at different modes

Mode Number	Natural Frequ-ency of Alumi-nium (Hz)	Natural Frequency of Titanium (Hz)	Natural Frequ-ency of Brass (Hz)	Natural Frequ-ency of Bright Plastic (Hz)
1	322.287	406.572	427.04	58.1909
2	912.327	1146.69	1199.85	166.172
3	1021.41	1288.12	1351.83	184.299
4	1121.77	1414.79	1486.05	202.637
5	1246.15	1571.91	1649.7	224.815
6	1327.22	1673.47	1749.32	238.04
7	1826.19	2310.88	2432.33	326.334
8	1982.08	2490.26	2595.78	359.57
9	2656.52	3316.56	3418.65	485.171
10	2781.54	3490.76	3631.51	505.454

DISCUSSION

Static Case Analysis

From Figure 3 and Table 2 it can be deduced that the Von-Mises stress in aluminium is at maximum (highest value) when compared to brass, titanium and bright plastic. Moreover, from table 2, it can be deduced that the deformation is minimum in brass when compared to aluminium, titanium, and bright plastic. From Figure 5, 10, 14, 18 and Table 2, it can be deduced that the displacement is maximum in bright plastic when compared to aluminium, titanium and brass. It can also be affirmed from Table 1 that maximum specific modulus in brass is maximum when compared to aluminium, titanium and bright plastic.

Frequency Case Analysis

From Figure 6, 12, 16, 20 and Table 3, it can be deduced that brass has the highest natural frequencies when compared to aluminium, titanium and bright plastic.

Cavitation damage is one of the major problem encountered by water pump. Irrespective of the hardness and toughness of the material, it is capable of removing material from the flow boundary surfaces. Materials with high value of Von-Mises stress can results to cavitation erosion which is detrimental to the surface layer of the metal. It can be deduced from Table 2, that aluminum and titanium (when compared to brass and plastic) are materials with the highest Von-Mises stress which makes them prone to cavitation erosion. In addition, high deformation value of the aluminium (0.0235mm), titanium (0.0242mm) and plastic (0.850mm) material (when compared to that of brass 0.0215mm) will adversely affect the pump performance since the pump will no longer operate on its initial design or curve.

CONCLUSIONS

Comparing the results of the static and frequency case analysis done for the water pump impeller for the four materials (aluminium, brass, titanium and bright plastic), it can be deduced that brass is the material with the minimum deformation when compared with aluminium, titanium, and bright plastic which implies an increase in the strength (also justified by its maximum specific modulus) of the pump and that chances of failure of the water pump impeller is less. From the results shown above, it can also be affirmed that the natural frequencies of brass is higher compared to aluminium, titanium and bright plastic, hence brass has higher strength compared to aluminium, titanium and bright plastic. In addition to being cost efficient, Brass are generally effective and easy to maintain. From this work, Brass is the best-suggested material for the design of impeller.

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