Study on Behavior of Water Treatment Pump Before and After Modification using Finite Element Modal Analysis

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Abstract. The aim of this study is to conduct a finite element analysis towards an existing water treatment pump and modification in order to reduce resonance. The application of water treatment pump is a way to inhale dirty water from the lower pressure to the high pressure area. Improvement and study about water treatment pump system to reducing the resonance with several modifications on the pump structure. Therefore, the pump will be designed to meet the requirement of the system. The basic concepts of available water treatment pumps were studied thoroughly. Designing with the actual measurements, the next step was to analyze the design using Finite Element Analysis (FEA) for simulations of natural frequency, static and dynamic analysis via Solidworks2017. It is to make sure that the system can function without any failure and to determine the vibration level due to resonance phenomenon. Result for modal analysis shows that the excitation frequency which experienced by the pump casing is 47.57 Hz and the natural frequencies are above 500 Hz which is too high. After adding damping system to the pump casing, the natural frequency reduced to 6.9286 Hz, 20.254 Hz, 9.477 Hz, 46.29 Hz and 71.819 Hz which in turn reduces the vibration. For rotary screw, natural frequencies were reduced when the material stiffness has been decreased from 74,000 N/m² to 72,400 N/m².

1. Introduction
There are several types of pumps used in industries such as centrifugal, propeller, turbo and positive displacement. Water treatment pump plays an important role in industries like petrochemical, to remove slurry from petroleum. Vibration and noise are the most common pump malfunctions caused by the interaction of multiple factors and various reasons[1]. Excessive level of vibration may cause severe damage to pump bearing, shaft, impeller and other relevant parts in the pump. In order to increase lifespan of the pump, several modifications can be made. A modal analysis on the water treatment pump will be carried on before the modifications takes place[2].

Based on the research, best pump modification could be obtained with these steps. The existing water treatment pump must be drawn in Solidworks2017 with its exact dimensions. Any modifications such as loosening structure, stiffening structure, adding mass, installing tuned absorber is recommended to be applied in order to prevent resonance. However, it is needed to be ensured that the modification can well reduce the vibration effectively and safely. Therefore, to conduct Finite Element Analysis (FEA), so best modifications can be properly implemented. This work is started by collecting data such as technical drawing of pump and structure, specification of motor and pump (including mass, RPM, etc.), and material specification of structure and pump[3]. It is necessary to include exact dimensions and parameters in order to get the actual pump based results. Afterwards, drawing and modeling of existing structure are carried out. Then by using Solidworks2017, several types of
modification such as loosening structure, stiffening structure, adding mass, or installing tuned absorber are performed. Solidworks2017 is one of the best software to design and analyze products in 3 dimensions. Many types of pump designs can produce by using this software in shorter period.

The general objectives of this research are to carry out modal analysis by using Finite Element Analysis to identify the resonance in water treatment pump. With the help of Solidworks2017 software, any mitigation such as loosening structure, and/or stiffening structure, adding mass, installed tuned absorber is to be applied in order to prevent resonance. The desire modifications can be well reduced the vibration effectively and safely. Finally to obtain the best modification of water treatments pump with less resonance phenomenon.

The natural frequencies and mode shapes of the pump are the modal parameters inherent in the system. These modal parameters affect the dynamic response and transmission of vibration. The modal parameters can be obtained by finite element analysis and modal analysis.

2. Finite Element Analysis

Finite element analysis is a computerized procedure for the analysis of structures and other continua. Rapid engineering analyses can be performed because the structure is represented (modeled) using the known properties of standard geometric shapes, i.e., finite elements. Efficient, large, general-purpose computer codes now exist with appropriate matrix assembler routines and equation solvers for calculation of the following structural properties:

a) Static displacement and static stress.

b) Natural frequencies and mode shapes.

c) Random forced response, random dynamic stress.

General purpose finite element codes such as NASTRAN, ANSYS, SAP, ADINA, Solidworks2017, etc., are programmed to develop and solve the matrix equation of motion for the structure:

\[ [M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=[F \cos \omega t] \]  (1)

The model details are entered by the analyst in a standardized format. The computer then assembles the matrix equation of the structure. The first part of the solution (1) to a given problem is to solve the matrix equation;

\[ [M]\{\ddot{u}\}+[K]\{u\}=0 \]  (2)

for the free vibrations of the structure. The solution to equation (2) gives the natural frequencies (eigenvalues) and the undamped mode shapes (eigenvectors). These parameters are the basic dynamical properties of the structure, and these parameters are needed for use in subsequent analysis for dynamic displacements and stresses [4].

Finite element analysis in conjunction with the high-speed digital computer permits the efficient solution of large, complex structural dynamics problems. As the majority of structural dynamics problems are linear and can be solved in the frequency domain using a modal transformation as noted above, subject to certain simplifying assumptions concerning the nature of damping.

The finite element method therefore offers a very efficient procedure for the calculation of complex linear structures under a variety of dynamic excitation conditions, and under environmental conditions, which may include temperature effects and entrained fluid effects. Where the structure is nonlinear, modal testing may still be used (with caution) to estimate initial values for mass, stiffness, and damping parameters, which can then be modified to suit more advanced structural models [5].

Although most linear structural dynamics problems may now be solved accurately and economically, it is still costly to solve most non-linear problems. For such cases a solution strategy
must usually be developed on a case-by-case basis. In such instances the structural geometry and elasticity may be needed in considerable detail in the input data, and the formulation time for such cases may be significant unless suitable pre-processors are available within the code. Efficient computation of such recurrent components has been undertaken by special finite difference procedures, but sub-routines to undertake such computations are not yet in widespread use [6].

3. Modal Analysis
An analysis which provides an indication of the limits of the response of a particular system is known as modal analysis. Basically every object can naturally vibrate with presence of an internal frequency (or resonant frequency) in the object. It is also the frequency where the object will allow transmission of energy from one form to the other with minimal loss – here vibrational to kinetic. It is better to know the structure of an object can behave unevenly with these frequencies [7].

Natural frequencies and mode shapes of structures can be identified by using formalized method which uses in modal testing. Modal test produces results such as various natural frequencies, mode shapes, and related data of the structure. In modal testing, data were collected using effectual curve fitting routines on the digitized input signals. The results will be animated which displays impedance plots and mode shapes. There were some cases where an earlier precise modal analysis have prevented loss to lives and property, in instance in case of an earthquake.

First, a modal test provides the most rapid and effective procedure available for the acquisition of data on the dynamic properties of a structure. Second, modal analysis is an effective analytical procedure for the solution of large sets of structural dynamics equations because it reduces coupled matrix equations (which must otherwise be solved by some iterative procedure) to a set of independent linear equations, each with the well-known closed-form solution given above. Modal solutions can therefore be obtained directly, without further numerical operations.

These solutions are then recombined to form the complete solution to the structural response problem in question. It should here be noted that solutions to harmonic, transient, and random forced vibration problems can all be obtained using this modal analytical procedure [8].

The main assumption involved in the acquisition of this information is that the structural system is linear, i.e., structural displacements are directly proportional to applied loads. In practical structures this condition is not always met. Structural systems may be non-linear to some degree, due to those causes listed below. Nonlinearities complicate the extraction of modal data and, where the effect is strong; it may invalidate the results obtained by linear analysis.

Non-linear effects complicate the analysis and tend to introduce errors into the data reduction and curve-fitting estimates of natural frequencies. Such results cannot always be adequately represented by a linear analysis, because the properties change according to the magnitude of the applied load [9].

4. Methodology
Good design requires both analysis and synthesis. Typically, approach complex problems like a design decomposing the problem into manageable parts. It is needed to understand how the part will perform in service and must be able to calculate as much about the part’s behaviour or possible by using the appropriate disciplines of science, engineering and computational tools [10].

Drawing and modeling of each modification is performed. Thus, it can be estimated which modification could shift the natural frequency far away from operating speed. After the best modification is obtained, static, dynamic and modal analysis will be conducted. Hence, it can be ensured that the modification is acceptable in material strength point of view, so it can be proposed to be implemented.

4.1 Measurements
Reference to redrew the water treatment pump and motor has taken from specification stated by the previous researcher. The measurements of water treatment pump which will be developed as follow:
Table 1. Measurements of water treatment pump.

| Parameters | Dimension (mm) |
|------------|----------------|
| Length     | 441            |
| Height     | 183            |
| Width      | 125            |

4.2 Preliminary Design

After considering the lowest reading on static analysis, the best design of pump will be selected among these 3 designs which is Design 1, Design 2 and Design 3. All three designs have different types of basement. Design 1 has two ‘T’ shape basement. While Design 2 has one ‘T’ shape basement attached in the middle. Lastly Design 3 has solid basement which attached from one end to another. The selected design will undergo analyses like static, dynamic and modal analysis using Solidworks 2017. Based on the results in Table 2, the best design for pump casing can be chosen was Design 1. By comparing the other two designs, Design 1 has the lowest reading on static stress which is 8.317 MPa compared to Design 2 & Design 3 where 35.155 MPa and 9.911 MPa respectively. The design which has lower static stress value is tend to last longer compared to design with higher value of static stress.

Table 2. Selection of pump casings.

| Static Analysis for Pump Casings |
|----------------------------------|
| Plot Type                        | Static stress N/mm² (MPa) | Static displacement (mm) | Static strain |
|                                  | Highest | Lowest    | Highest | Lowest    | Highest | Lowest    |           |
|                                  | Design 1 | 8.317     | 0.001   | 0.012     | 0.000   | 2.23x10⁻⁶ | 6.15x10⁻⁹ |
|                                  | Design 2 | 35.155    | 0.004   | 0.380     | 0.000   | 1.23x10⁻⁵ | 4.885x10⁻⁴ |
|                                  | Design 3 | 9.911     | 0.001   | 0.011     | 0.000   | 2.69x10⁻⁶ | 5.86x10⁻⁴ |

4.3 Pump Modifications

There were two modifications have been made onto the water treatment pump. First, pump casing was added with 2 springs at the bottom. Those springs act as a vibration damper in order to reduce the amount of vibration. Second modification was made on the rotating screw. The material of rotating screw was changed with material which has less stiffness. This will tend to reduce the natural frequency of rotating screw. Figure 2 shows the parameters applied on pump casing such as fixture, pressure, spring stiffness and gravity.

Figure 1. Parameters applied on pump casing.
There were two components of product will be analyzed which are pump casing and rotary screw. For the pump casing and rotary screw, the load of 10 kN/m$^2$ is put on the pressure area. Spring stiffness of 12,500 N/m was added to the pump casing [11]. Fixtures were charged at the bottom of base. Gravitational force of 9.81 m/s$^2$ was added vertically. Due to the whole pump structures were made of steel, the damping ratio equal to 2% was added in the analysis [12].

4.4 Finite Element Analysis

Based on Figure 2, von Mises stress indicates 6.174 MPa on pump casing which is lower than the previous unmodified pump casing which is 8.317 MPa. The springs below experience more von Mises stress compared to pump casing. The highest value of stress in this analysis is 142.742 MPa.

Figure 2. Static stress of modified pump casing.

According to Figure 3, von Mises stress indicates 5.156 MPa on rotary screw which is lower than the previous unmodified rotary screw which is 5.320 MPa. Moreover, this modified rotary screw has von Mises stress which is below the yielding strength 345 MPa.

Figure 3. Static stress of modified rotary screw.

5. Result and Discussion

The analysis in Solidworks2017 is about to know the stress, displacement, strain, mode shape and natural frequency when parameters such as pressure, gravitational force and other related loads are applied.

Based on Table 3, results obtained for static analysis on pump casing can be concluded as modified pump casing has small amount of von Mises stress of 6.174 MPa experienced on its structure compared to existing pump casing which is 8.317 MPa. So that, modified pump casing tend to have
less vibration compared to existing pump casing. Meanwhile for rotary screw, can be concluded as modified rotary screw has obtained lower von Mises stress of 5.156 MPa compared to existing rotary screw which is 5.320 MPa. So that, modified rotary screw tend to have less vibration compared to existing rotary screw.

Table 3. Comparison results for static and dynamic analysis.

| Plot Type       | Static Stress N/mm² (MPa) | Dynamic Stress N/mm² (MPa) |
|-----------------|---------------------------|----------------------------|
| Plot Type       | Highest                   | Lowest                     | Highest                   | Lowest                     |
| Static stress   | 8.317                     | 0.001                      | 8.1122                    | 0.017                      |
| Static displacement (mm) | 6.174         | 0.000                      | 0.631                      | 0.004                      |
| Static Strain   | 5.320                     | 0.004                      | 35.64                     | 0.017                      |
| Dynamic displacement (mm) | 5.156        | 0.000                      | 81.12                   | 0.000                      |

Results shown on Table 3 for dynamic analysis proves that modified pump casing experience less vibration compared to existing pump casing. Von Mises stress on modified pump casing indicates only 0.631 MPa which is very much lower compared to existing pump casing, 81.122 MPa. Then by referring to the results for rotary screw, it can be concluded as modified rotary screw has small amount of von Mises stress experienced on its structure which is 31.31 MPa compared to existing rotary screw, 35.64 MPa. So that, modified rotary screw tend to have less vibration compared to existing rotary screw.

According to graph shown in Figure 4, the value of natural frequency dropped drastically after adding vibration damper (springs) at the basement of pump casing. These springs will isolate vibration in the pump casing by absorbing the energy in one way and release it in another. A good vibration damping system will lower the natural frequency of pump casing below excitation frequency. The excitation frequency which experienced by the pump casing is 47.57 Hz and the natural frequencies are above 500 Hz which is too high. After modification have made, the natural frequency reduced to 6.9286 Hz, 20.254 Hz, 9.477 Hz, 46.29 Hz and 71.819 Hz. The new natural frequencies at mode shape 1, 2, 3 and 4 are below the excitation frequency 47.57 Hz which in turn reduces the amount of vibration.
Mass = 4.56358 kg
Volume = 5.8572106x10^{-4} m^3
Stiffness = 1x10^{10} N/m^2 or 10,000 MPa

Mass density; \( \rho \) = \frac{Mass}{Volume} = \frac{4.56358 \text{ kg}}{5.8572106 \times 10^{-4} \text{ m}^3} = 7791.39 \text{ kg/m}^3

Natural frequency; \( \omega \)

\[
\omega = \sqrt{\frac{k}{m}} = \sqrt{\frac{1 \times 10^{10} \text{ N/m}^2}{7791.39 \text{ kg/m}^3}} = 1132.90 \text{ rad/sec}
\]

Conversion of radian per second to hertz:

\[
\omega = 2\pi \nu
\]

\[
1132.90 = \frac{2\pi \nu}{2\pi} \Rightarrow \nu = 180 \text{ Hz}
\]

The results obtained for natural frequency via manual calculation is too high (180 Hz) compared with results obtained through simulation. It is an acceptable value because when the number of mode shape increases, the value of natural frequency also increases.

Natural frequencies of modified rotary screw which is shown in Figure 5 are lower compared to unmodified rotary screw. Natural frequencies were reduced when the material stiffness has been decreased from 74,000 N/m^2 to 72,400 N/m^2. According to the natural frequency formula, when material stiffness was decreased or material mass was added, natural frequency will decreased.
Although the natural frequency of modified rotary screw is still higher than excitation frequency (47.57 Hz), the values of natural frequency has been successfully reduced which means the vibration level is also reduced.

6. Conclusion
This study is to carry out modal analysis by using Finite Element Analysis to identify the resonance in water treatment pump using Solidworks 2017. Then to obtain the best modification of water treatment pump with less resonance phenomenon. In order to reduce resonance, modification such as adding damping system (springs) and changing material had been implemented.

The simulation analysis showed in detail about static analysis, dynamic analysis and modal analysis for both existing and modified water treatment pump. The obtained data proves that the resonance can be reduced by adding damping system and also by changing material of the body structure. It is hoped in reality, these kinds of modifications will help to reduce vibration and resonance in the water treatment pump. By modifying it, the lifespan tend to increase. Besides that, no need to frequently do preventive maintenance and it will lead to reduce the unnecessary maintenance cost.

The recommended modifications to reduce vibration on a pump are:
1. Adding vibration damper like springs at the base of pump. To obtain a better vibration reduction rather than using spring it is recommended to use rubber, polyurethane or sorbothane. Comparing to spring these 3 materials can isolate and damp vibrations.
2. Reducing the material stiffness or adding material mass.

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