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An Integrated Study for Solving High Vibration Problem of a Deep Well Turbine Pump

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Abstract: In this study, a deep well vertical turbine pump experienced extremely high vibrations for a long time although it still being new. It hasn't been in operation for over 6 months. A novel strategy is implemented by using well-conceived techniques. The experimental modal analysis is confirmed a presence of a natural frequency. Modifications are carried out to overcome resonance. Finite element analysis is applied to determine the reed critical frequencies as a powerful tool to identify and mitigate vibration issues. On-site motor balancing is done to remove vibrations due to the residual imbalance. Results reveal decreasing vibration level by about 8% after solving all problems.

Keywords: Vibration analysis, finite element analysis, modal analysis, resonance, vertical turbine pump

1. Introduction

Many field applications depend on the usage of vertical turbine pumps such as irrigation, power generation, and petrochemical industries. These pumps can vibrate and respond because of any excitation force. An unbalance problem is the most important defect that could be occurring in all rotating machines which produces a severe dynamic effect. Hydraulic unbalance as well as mechanical unbalance has the same impact most times [1]. If the rotating element axis are not matching with the rotating shaft axis, mechanical unbalance will occur. Unbalance forces always occurred at rotor speed (1rpm), so it has a sine wave as seen from references [2]. Vertical turbine pumps have been used in many applications such as irrigation, water supply, and petrochemical industries. All turbine pump system parts vibrate in reaction to the forces of excitation. Unbalanced mass related to the mechanical and hydraulic performances of any pump are important elements that produces vibrations. The produced hydraulic forces ensuing because of hydraulic unbalance have a comparable impact as mechanical unbalance. For best pump operation, mechanical vibrations related to the pump need to be inside standard limits. A better vibration levels now no longer best ends in operational loss, however, additionally ends in downtime because of untimely failure. Therefore, it's far of critical significance to recognize the main reason for unbalancing pressure and its reason [3]. The unbalance is one of the most problems encountered in the pump system. Many parameters should be noted to diagnose the unbalance problem by using vibration analysis [4]. In many fields, pumps should be tested for high vibration levels to determine if it operates within the permissible limits or not. It is vital to perceive the reasons for vibration and strategies to minimize the identical to make certain the security and operation. Vibration sources may be especially from mechanical and hydraulic issues. Mass unbalance is the main source that causes dynamic impacts and dangerous excitations. These forces lead to unwanted vibrations and noise [5]. Numerical analysis is a vital tool for troubleshooting vibration problems in vertical pumps. Also, it helps to find good solutions for any applications. The effects of any structural corrections on the resonance are obvious and benefit reaching the optimum status. The stiffness of the initial baseplate has numerically increased, so the resonance shifted away from 1X speed [6]. Modal analysis is a technique that is carried out for predicting the dynamic characteristics of vertical turbine pumps. Structural modifications could be achieved by

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changing mass or stiffness at specified places depending on the natural frequency and how it is close to the pump operating speed [7]. Detection of unbalance of rotating shaft is presented through achieving the deflected shape. Any variation of the shaft deflection is considered as a sign of the presence of unbalance. This method is considered as a new one used for detecting and diagnosing the unbalance problem in rotating machines [8]. A problem of high vibrations is detected due to operating the pump near the natural frequency of the system. Efforts are exerted to mitigate high vibrations. Many tests are conducted to lower or raise the natural frequency below the operating speed. The solution for this problem is achieved by applying a rigid mounting with the neoprene isolation pad [9]. It is necessary to determine the vibration characteristics of the vertical pumps before assemble to avoid resonance problems. A mathematical model is proposed to evaluate the effect of the foundation on the pump characteristics. Validation of the model is conducted sing experiments and simulations [10]. Determining of vertical centrifugal pump vibrations at various parameters is studied using MATLAB. Results are compared with machinery fault diagnosing chart to indicate the type of every problem [11]. Vibration problems could be a main cause of reducing pump efficiency from its best efficiency point. Design modifications are implemented to overhung centrifugal pump feet to enhance the dynamic performance and service life [12]. Vibration analysis and diagnosis of water treatment pump are presented by the combination of modal testing and short time auto regressive method. Pump dynamic behavior is evaluated from experimental analysis during normal operation. It is confirmed that vibration measurement analysis is an effective tool for evaluation of such huge machines [13]. Diagnosis of the vibration source at a vertical pump is experimentally and numerically obtained. Impact test is carried. Numerical and experimental results of modal and harmonic analysis were closed. Modifications are done on the coupling cover to avoid natural frequency and mitigate vibrations [14]. An investigation is done to analyze vibration state of a vertical pump. Early detection of bearing defect and cavitation problem is carried by implementing the vibration analysis technique [15]. A vibration problem was encountered at a vertical turbine pump. The main cause of vibrations was the pump system structure and misalignment between motor upper and lower base part of the pump. The solution was to shift the structural resonance and reduce the amplitude of the operating vibration [16]. Vibrations are analyzed to identify dynamic characteristics of a vertically suspended pump. Spectrum analysis is carried to indicate the root cause of impermissible vibrations. Mechanical looseness is found to be the main cause of the problem. Investigation for a solution was to correct the loose mounting bolts [17]. High vibration causes of declining vertical pump are identified. The main cause was the foundation weakness. Modification is applied by adding steel supports to motor foundation gradually [18]. A large vertical pump is experimentally and analytically studied. Many numbers of vibrational moods could be found near the running operation speed and my cause resonance. Various case histories included to indicate the dynamic problems that could be encountered with vertical pumps [19].

The rest of this study is organized below. In Sect.2, the problem statement is considered. In Sect. 3, the evaluation of the current dynamic state is introduced. In Sect.4, the experimental model testing analysis is presented. In Sect.5, the finite element analysis is introduced. In Sect.6, the analysis of unbalance problem is presented. In Sect.7, a discussion is shown. In Sect.8, the conclusions of this study are drawn.

2. Problem Statements

A vertical turbine deep well pump is a circular water pumping system. It is mostly a vertical single-suction multistage centrifugal pump. The impeller is installed under the moving water level in the water well. A deep well vertical turbine pump driven by an induction motor experienced chronic recurring high vibration. It has recently been overhauled and installed to operate a deep well. High vibration levels in the motor reached 25 mm/sec at 1X motor dominant vibration component. Station working experts had an explanation for this problem, which they attributed to their causes to be completely structural. This entails applying some structural modifications that were done quickly and thoughtlessly. Many attempts were achieved by station experts to minimize impermissible levels, such as welding braces to the pump structure. These modifications did not indicate any good results and vibration levels were still as high as before. This research is an attempt to investigate the main causes of the high vibration and determine the source of this problem to return to acceptable levels of operation. Firstly, an evaluation of the pump's current condition should be applied. Moreover, it is necessary to ensure if there is a presence of resonance or not, to ensure the integrity of the structural modifications that are made to the system. Then determine if there were any other reasons for the high vibrations.

3. Evaluation of The Current Dynamic State

If the vertical turbine pumping system suffers high vibrations, it is very important to diagnose the problem as fast as possible to avoid any malfunctions. This may need advanced and precise equipment to measure and diagnose vibration parameters.

Visual observation at the motor non-drive end showed excessive vibrational movement. It was very important to ensure all mechanical assembly integrity before applying any measurement to reveal that the motor pump system was generally installed correctly. Firstly, the connection between the motor and the pump via coupling was separated to examine the measurements at no-load conditions. Also, measurements were applied at full load conditions. All measurements have been carried out in the axial, vertical, and horizontal directions. The accelerometer is connected to the portable vibration analyzer. By the Fast Fourier Transform (FFT) technique, all the signals collected in as a time signal are processed and changed into the frequency domain. This will be easy to analyze and diagnose.

Measurements were done on the pump parts during normal operating conditions. It is necessary to determine exciting forces and explain if their source is due to resonance or not. Measurements indicated that during no-load conditions the vibration levels had extremely increased, especially in the radial directions of motor non-drive end.

Measured vibration levels at no load and full load are shown in Fig. (1). It reached about 25mm/s and 20mm/s at full load and no load respectively. It is dander and not permissible to operate the pump in this state. It was obvious that vibrations during full load are larger than those at no-load at the same locations. However, the maximum vibration level measured at the full load pump unit increases by about 25%. However, operating the pump system at full load conditions generates other sources of unwanted vibration. Reconnecting the motor to the pump system has a slight influence of the motor's vibrations. This revealed that the source of vibrations is coming from the motor itself, regardless connecting to a load or not. High measured vibrations are at the motor non-drive end in the radial direction, and also on the upper and lower guide bearings showing excitations locations. Because of excitation sources of the motor non-drive end bearings, vibration at these locations is usually alternating due to the presence of faults and problems at these locations. The operating pending such conditions increase vibrations and may lead to sudden breakdown.

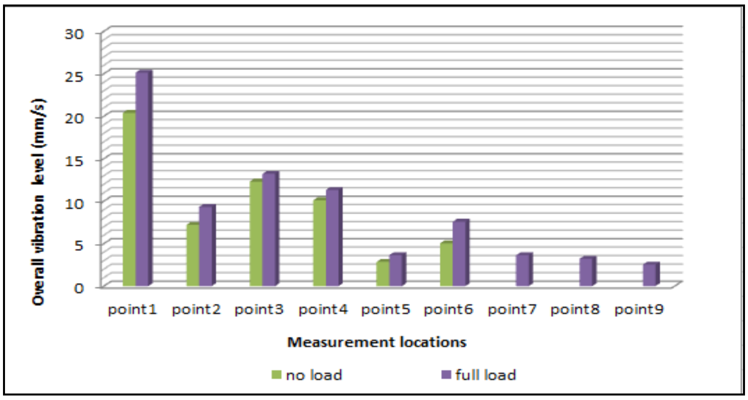

Fig. 1 - Measured vibration levels during no-load and full-load

Frequency analysis was carried out in the axial and radial directions to specify the excitation frequencies and determine high vibration sources. Similar to the previous results, the motor non-drive end has higher vibrations. The vibration spectrum at full load condition is indicated in Fig. (2), which represents high vibration amplitudes in the vertical and horizontal directions with maximum amplitudes of 24.3 mm/s and 29.2 at the motor rotating speed (49.1 Hz). While Vibration spectrum at no-load conditions is indicated in Fig. (3), which showed high vibration amplitudes in the vertical and horizontal directions with maximum amplitudes of 14.6 mm/s and 9.32 at the motor speed. Based on these results, it was obvious that the higher vibration origin is coming from the motor itself, whether it is connected to a load or not. It's well known that these severe vibrations can destroy bearings and causes shaft failure and downtime. Resonant machine components and supporting structures may be extended, although any slight vibration is enough for machines to malfunction or cause machine failures. The solution to this vibration issue should be quickly applied to avert such consequences. The most essential first step is to define while the origin of the increased vibration is a resonance problem with the rotating machine or the structure.

Resonance in pumps and motors could be happened when a natural frequency is near a forcing frequency such as running speed. This state can cause extreme vibration levels by mitigate little vibration forces produced from operating machine. Solving this problem is relying on the ability to differentiate between structural resonance and a presence of critical speed. So, it is very important to define if the origin of severe vibration via related to structural resonance or not. Depending on all of the above, it's far vital to use more specialized strategies to determine the problem issue. It must be checked if the source causing the high vibrations is the presence of resonance. An impact test was performed on the pump unit to determine the natural frequencies.

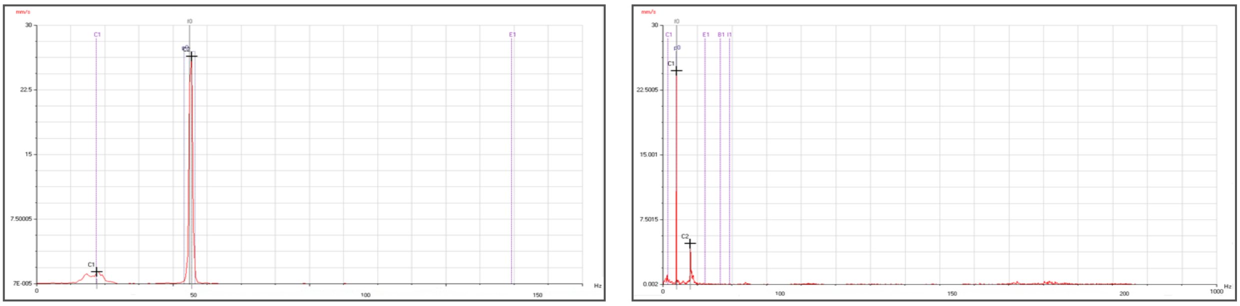

Fig. 2 - Vibration spectrum at full load condition in axial and radial directions

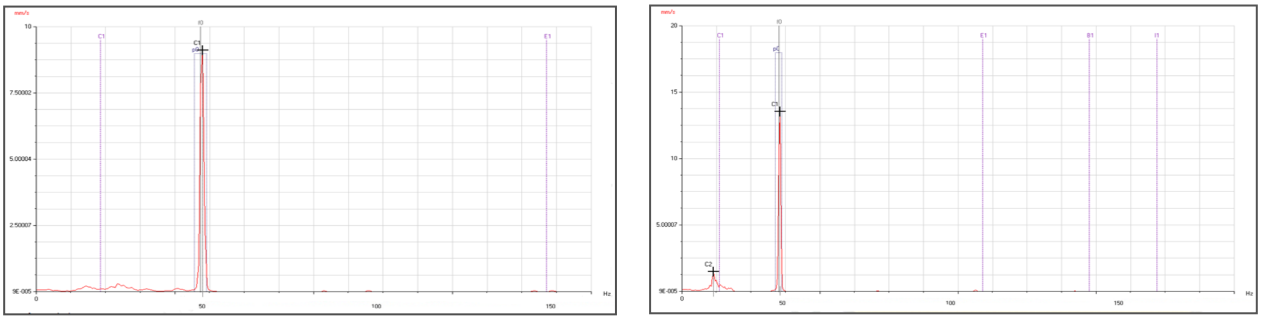

Fig. 3 - Vibration spectrum at no load condition in axial and radial directions

4. Experimental Modal Testing Analyses

The impact test is a test used to determine the structural natural frequencies of any structure. This test is also known as a bump test. This test requires that the pump be stopped and hit with an impact hammer that has a soft tip. This test provides a response curve that will determine the natural frequency of the pump. To apply the one direction test, it should be parallel to the pump discharge pipe and the other direction should be perpendicular to the discharge pipe.

This measured vibration data can be indicated as a higher natural frequency from that direction. The other direction which is perpendicular to the pump discharge will usually have a lower industrialist typically eliminates a part or more of the structure. This allows entering into the coupling or seal which also demoralizes the structure in that direction. To carry out impact testing, it is necessary to use a portable analyzer. The test was applied to the motor when it was shut down. The pump test shows two natural frequencies detected at 43.1 Hz and 55 Hz in two planes as shown in fig. 4. If the natural frequencies fall between 20% of the allowable working speed range, any slight force could be significantly amplified. The occurrence of resonance relies on the natural frequencies and how they are close to the rotation speed or any exciting frequencies. So, the solution was to move the natural frequency of the system far away from the pump speed. This will decrease the amplification factor radically. However, the natural frequency of any system is a function of its mass and stiffness. Changing mass or stiffness is a reliable way to solve the resonance problem. This could be carried out through increased mass and decreased stiffness or vice versa. Many trials were done to decrease these high levels of vibrations. A total weight of 50 kg was added to the structure in addition, all bolts in the body flange were tightened well to the concrete base.

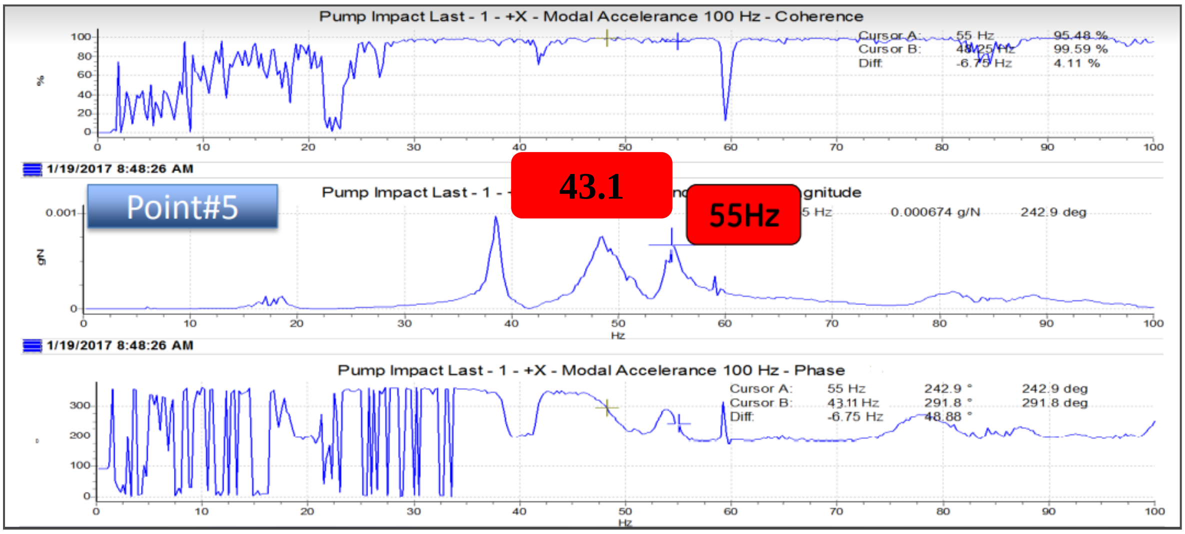

Fig. 4 - Impact test results showing main natural frequencies

After applying the new modifications, it was illustrated that the vibration amplitude at the pump running speed was reduced as shown in fig. (5). Vibration amplitude reaches 16.20 mm/s and 10.51 mm/s in the vertical and horizontal directions. Amplitudes decreased about 39% in the vertical direction while it decreased about 48% in the horizontal direction. It is noticed that despite all modifications Vibration levels remained high. The higher vibrations are still being in the motor, pump system with 1rpm motor dominant frequency. These results confirmed that there is another source of high vibration rather than resonance. So, If the motor pump system assembly reed critical frequency exists in the speed domain of the pump, high vibrations can produce. The next step is to conduct a modal calculation, in this case using a finite element analysis model.

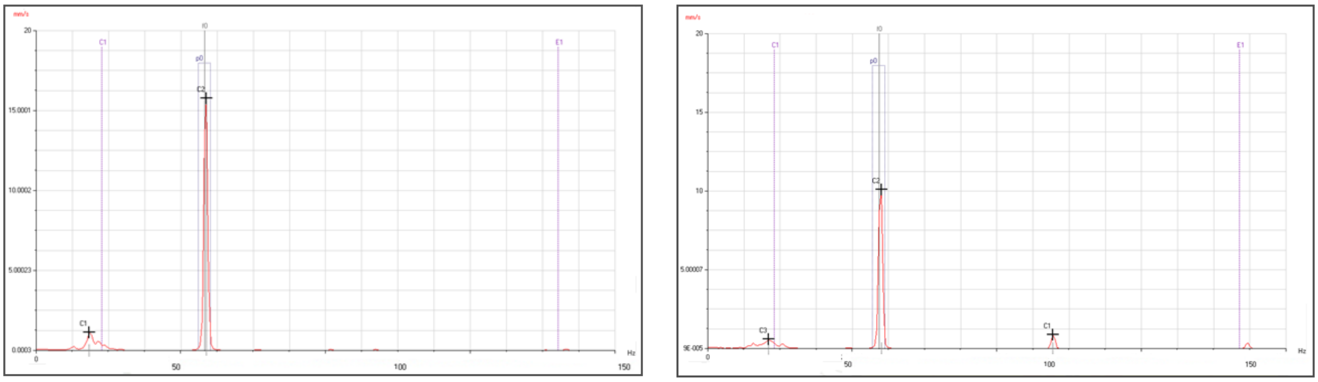

Fig. 5 - Vibration spectrum measured in the axial and radial directions after applying modifications

5. Finite Element Analysis

Vertical turbine pumping systems is long cantilever-type structures that have mechanical natural frequencies (MNFs) which can take place at pump speeds producing resonant vibration states. These natural frequencies are also named reed critical frequencies (RCFs) because the mode shape looks like a cantilever model. If the motor- pump system reed critical frequency happened in the speed range of the operating pump, high vibrations can happen. RCF analyses can be implemented at the design step for a new synthesis, field-installed stages, and installations already out in the field. To determine the effect of a critical natural frequency happening within the normal running speed range of the pump, modal analysis has been performed. The scope of an RCF Analysis includes the creation of a motor - pump system (FE) model. This analysis is achieved by using ANSYS 14.5 to define the natural frequencies and mode shapes. The material specified is structural steel with properties of elastic modulus E=210 GPA, Poisson ratio=0.3, and Density=7850kg/m3. The automatic mesh method was used to mesh the structural model of the system as shown in fig. (6). Boundary conditions assumed that the pump system was supported by tightening bolts as shown in fig. (7). Results indicated that, for the operating condition, the 1st mode (199.2 Hz) is away from the operating speed (49.1 Hz). The mode shapes of the system display some dominant circulation motion as shown in fig. (8). This circulation motion is always due to motor rotor residual unbalance. Awareness should be paid to this part in the analysis of vibrations that occurs in the pumps which are mounted vertically. Since the back part of the motor is not mounted on anything else, the

1X vibration exists in the motor. When defining the motor unbalance, 1X measurements should be carried out firstly by removing the coupling and operating the motor alone, to isolate the unbalance of the motor from the unbalance of the pump. In this case, the problem is in the motor if 1X levels of the free side of the motor are high. Otherwise, the problem is in the pump. While analyzing the vibration spectra, vibration peaks showing unbalance in the radial and axial directions should be compared. It was obvious that vibration peaks in the radial direction have higher amplitude than the vibration peaks in the axial direction. The extreme of the imbalance will be indicated by how close are these peaks in both. So, more post-analysis needed to solve this problem.

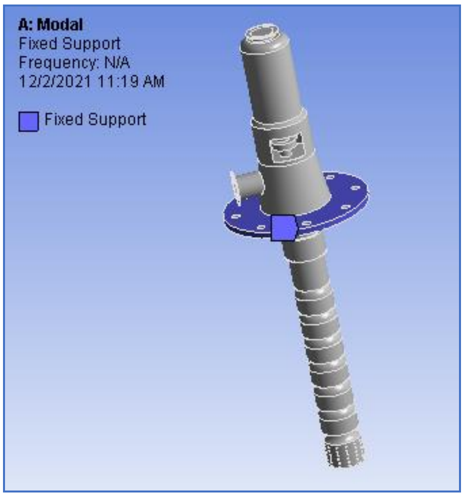

Fig. 6 - Mesh model of the pump system

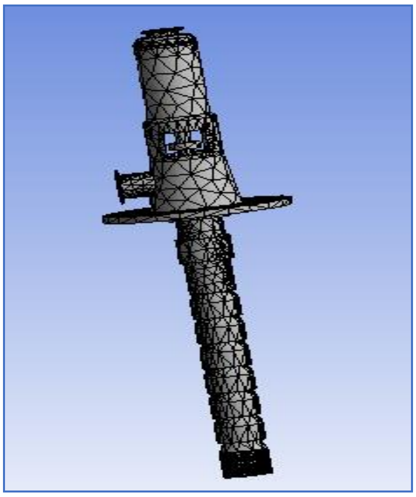

Fig. 7 - Model boundary conditions

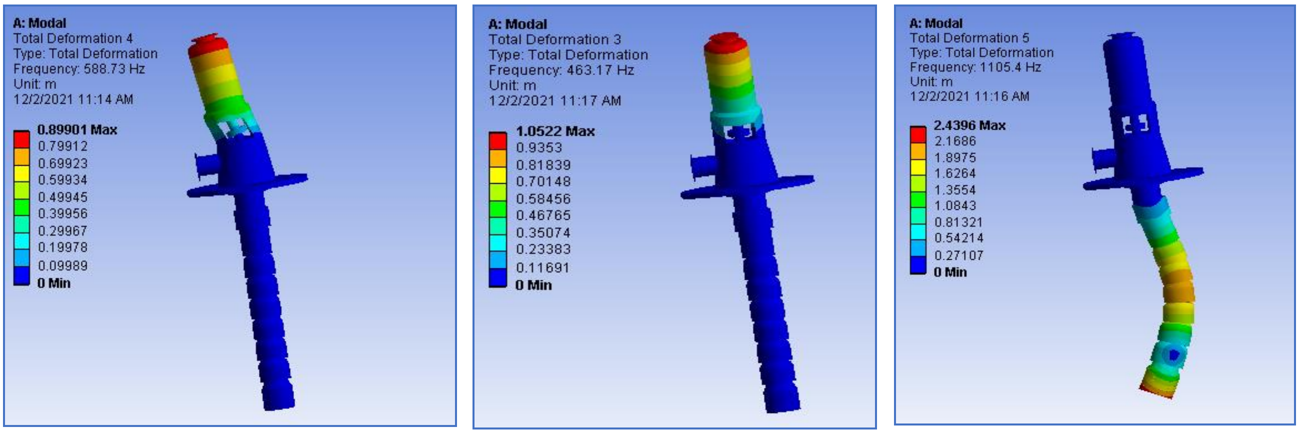

Fig. 8 - Mode shapes indicate the circular motion of the model

6. Analysis of Unbalance Problem

The unbalance is determined as that force due to a non-homogeneous distribution of the mass around the axis of rotation. The shaft inertia axis does not coincide with the rotation axis. This force affects the bearings. Balancing is the act of making the effective mass of a rotating component statically and dynamically equal about its rotating axis. If necessary, adjustment was done by adding or detracting weight to confirm that the vibration of the forces acting on the bearings is within acceptable limits [11]. The presence of small amounts of unbalancing in high-speed machines may confirm to be harmful, causing sudden tragic malfunction of any equipment more before the predicted lifespan. Overhung rotors are found in many field applications such pumps, fans, propellers, and turbomachinery. Vibration resulting from unbalancing can cause deterioration to important machine elements such as bearings, coupling, seals, etc. [12].

Problem of unbalance is the mainly source of vibration. It always produces force at machine rotation speed 1 X RPM. This presents some degree in nearly all rotating machines. Polar Plot analysis is a method to determine the unbalance in the machine. According to the nature of the plots, it could be easily determined the type of fault in the machine and can take remedial action immediately to prevent any catastrophic effects on the machine. Plot zero Polar Plot indicates data in polar coordinates helps to see phase changes in the range of zero to 360 degrees. The polar degree point is ever set at the angular position of a transducer. Collected data could be compared from perpendicular-mounted proximity probe pairs with a polar plot. Polar plots confirmed the presence of a high amount of residual imbalances response on the motor during crossing the critical speed in the resonance loop. From the polar plot analysis, it is evident that there exists a phase difference of 90 degrees for unbalanced fault in each direction of the bearings as shown in fig. (9).

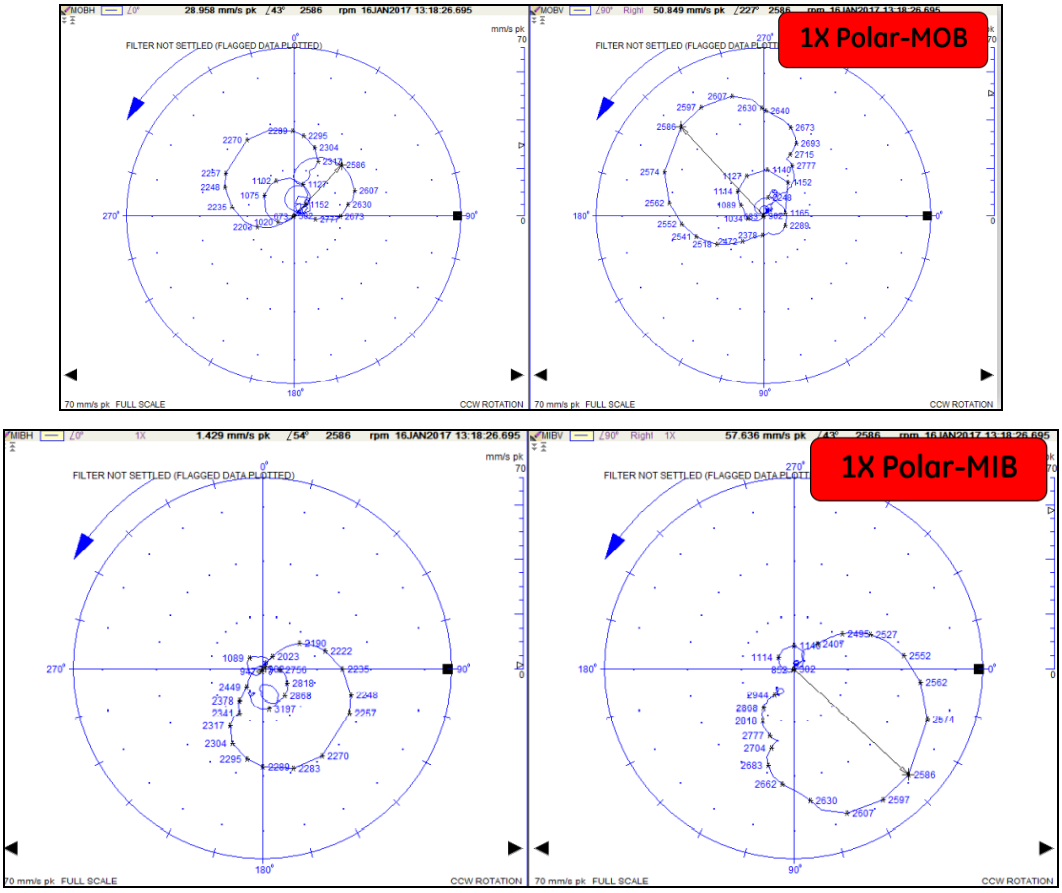

Fig. 9 - Polar plot response indicating resonance loop

The right decision was to implement on-site motor balancing. This was planned to eliminate the excitation force, which resulted in good findings. Results showed up a fault in balancing procedures applied by a local vendor at the workshop. The balancing shot is carried by adding up a hole weight of 178 g of the motor coupling hub (2 bolts were attached to the hub). The desired final balance shot was 210 g per vector calculations (at this balance plane; hub). There is no possibility to add last balanced weights on the hub. The polar plot shown in fig (10) indicated weights added to the coupling hub. A distinct reduction in the vibrations was detected in the pumping system. The amplitude reached 3.22 mm/s and 3.50 mm/s at the radial and axial. Vibration level decreased by about 80% at the vertical direction, while it decreased by about 66% in the radial direction. Fig (11) indicated the development of vibration level from the beginning of the existence problem until the completion of the solving process.

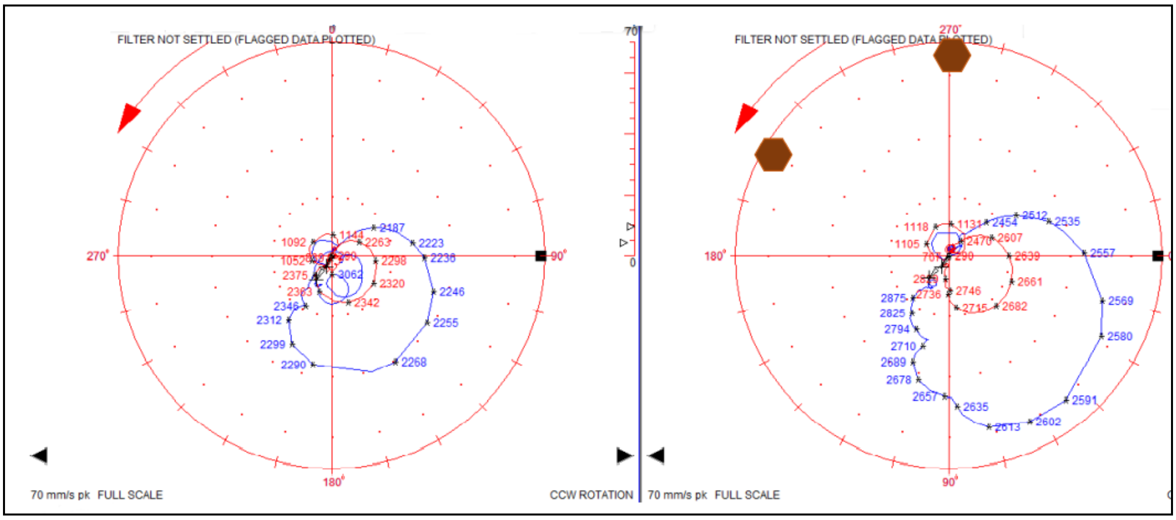

Fig. 10 - Polar plots indicated added weights

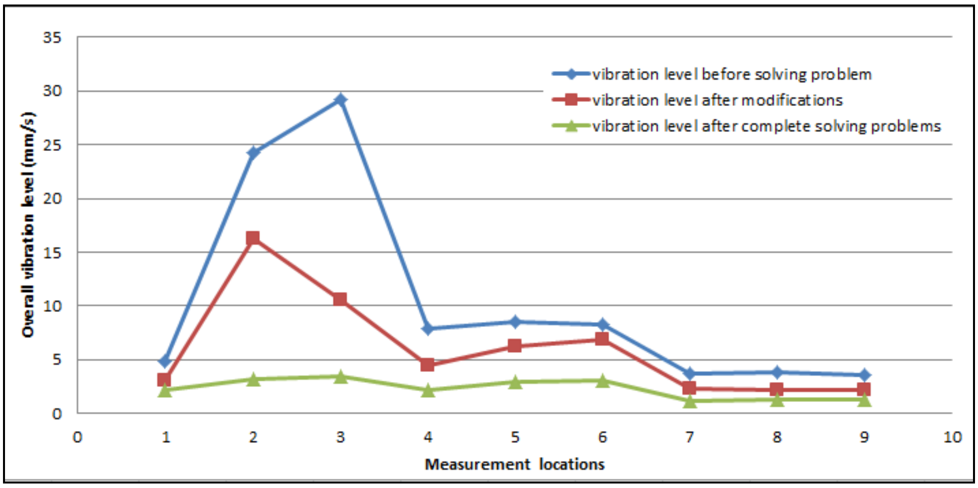

Fig. 11 - Overall vibration level during stages of solving problem

7. Discussion

Mechanical vibrations are a common problem encountered in many machines, especially for vertical turbine pumps. These pumps are generally difficult to stiffen or damp, but the effective diagnosis must begin with an understanding of the underlying vibratory sources. For instance, A. Y. Nikumbe et al. [6] Discussed the modal analysis of a vertical turbine pump analytically and experimentally. Verification between analytical and experimental results only carried out. Ensuring safety of pump operation is depended only on comparing the natural frequency with an operational frequency of the pump. Donald R Smith et al. [9] Dealt with a case study of high vibrations detected due to operating the pump near the natural frequency of the system. Efforts are exerted to solve the resonance problem, just experimentally. The field tests indicated the effectiveness of the neoprene isolation pad in lowering the system natural frequency that minimizes the vibrations. S. Ahilan et al [17] analyzed vibrations of vertically suspended Process pumps to identify natural frequency and also to check whether the pump vibrations are within allowable limits. FFT spectrum measurements are obtained only experimentally on the site to indicate the root cause of vibrations. Sami A. A. El-Shaikh [18] identified the causes of the high vibration the inclined vertical pump. The main cause was the foundation weakness. Frequency analysis used to determine the sources of vibration. Steel supports are added gradually to motor foundation gradually to fix the problem. No analytical analysis is conducted. In this study, an integrated strategy is implemented to solve a field problem encountered with a vertical turbine pump. The study took into account the completion of all the shortcomings in the previous research, so that it would be an integrated study. The study introduced full diagnosis of the pumping system condition before and after solving the problem. Full experimental and analytical analysis is conducted to determine the origin of the problem. A powerful tool is used to identify and mitigate vibration issues through well-conceived solutions.

8. Conclusions

Mechanical vibrations are a common problem encountered in many machines, especially for vertical turbine pumps. These pumps are generally difficult to stiffen or damp, but the effective diagnosis must begin with an understanding of the underlying vibratory sources. In this study, a reliability strategy is used to solve a dangerous problem associated with a vertical turbine pump. This problem could lead to sudden breakdown of the pump system if it is not resolved in a deliberate and planned manner. The work strategy in this study is depending on using highly reliable methods to solve the problem and eliminate the excessive vibrations. The preliminary results of the measurements confirmed that the level of vibrations reached dangerous and unacceptable levels. At the first stage, the solution of the problem depended on moving the natural frequencies of the system far away from the pump speed. Modifications are carried out through increased mass by adding a specific weight to the structure. At the second stage, further analysis is carried out by using a finite element model to determine the reed critical frequencies. At the final stage, on-site motor balancing was implemented to eliminate the excitation forces which resulted in good findings. In this study, a precise experimental measurement, simulation, and analysis helped to discover and accurately identify the problem. This undoubtedly leads to faster repair of the problem and a reduction in downtime. This strategy could be adopted to solve vibration problems of all vertical pumps for increasing performance, efficiency and reducing waste of energy and money.

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