Article citation info:
El-Gazzar DM. An integrated study for solving high vibration problem of a deep well turbine pump. Diagnostyka. 2023;24(2):2023209.
https://doi.org/10.29354/diag/166096.

DIAGNOSTYKA, 2023, Vol. 24, No. 2

e-ISSN 2449-5220
DOI: 10.29354/diag/166096

AN INTEGRATED STUDY FOR SOLVING HIGH VIBRATION PROBLEM OF A DEEP WELL TURBINE PUMP

Dalia M. EL- GAZZAR

Mechanical and Electrical Research Institute (MERI), National Water Research Center (NWRC). Egypt
e-mail: dalia_engdalia@yahoo.com

Abstract

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 the present work, 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. The pump system suffers from extremely high vibration levels relative to the rotational speed (1X motor dominant frequency). An efficient strategy was implemented by using well-conceived techniques. The experimental modal analysis confirmed a presence of a natural frequency. Modifications were carried out to overcome resonance. Finite element analysis was done to determine the reed critical frequencies as a powerful tool to identify and mitigate vibration issues. On-site motor balancing was done to remove vibrations due to the residual imbalance. Results revealed decreasing vibration level by about 66% after solving all problems.

Keywords: vibration analysis, Finite Element Analysis, modal analysis, resonance, vertical turbine pump.

1. INTRODUCTION

Unbalance is considered one of the most common problems encountered in rotating machines, posing an extreme risk to the system's lifestyles and operations [1]. All the time unbalance is always occurring because of the incompatibility between the geometric and inertia axis of the system. Rotor unbalance generates a significant vibration that occurs at the rotating frequency. This resulted in shaft deflection and stresses which affect the operating frequency of the system [2]. Coupled unbalance has many dangerous effects. When the operating system is working under an unbalanced effect, the possibility of generating high vibration increases. Many consequences may be occurring like excessive noise, vibrations, and stress. This decreases the reliability of the operating system and may lead to sudden breakdowns [3]. 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 have the same impact most times [4]. If the rotating element axis is not matching with the rotating shaft axis, mechanical unbalance will occur. Unbalance forces always occurred at rotor speed (1rpm), so it has a sinusoidal wave of time when seen from a stationary frame of reference [5]. Vertical turbine pumps have been used in many applications such as irrigation, water supply, and petrochemical industries. All turbine pump system parts can vibrate in reaction to excitation forces. Mass unbalances related to the mechanical and hydraulic geometry of a pump are the two important elements that create pump vibrations. The generated hydraulic forces ensuing because of hydraulic unbalance have a comparable impact as mechanical unbalance. For the best operation of the pump, vibrations related to the pump need to be inside the proper limits of relevant standards. A better stage of vibrations now no longer best ends in operational loss, however, additionally ends in downtime because of untimely failure. Therefore, it's far of critical significance for product designers to recognize the dominating reason for unbalanced pressure and its source [6]. 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 [7]. 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 best operation of a pump. Vibration causes may be especially of mechanical and hydraulic nature.

Unbalance masses are the major source that causes dynamic impacts and dangerous excitations. These forces lead to unwanted vibrations and noise [8]. 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 have numerically increased, so the resonance has been shifted away from 1X operating speed [9]. Modal analysis is a technique that is carried out for predicting the dynamic characteristics of vertical turbine pumps. Structural modifications could be achieved by changing mass or stiffness at specified places depending on the natural frequency and how it is close to the pump operating speed [10]. for the solution of vibration problem it should have some knowledge of pump operation and working and the possible causes of vibration in pump. some basic causes of vibration in pump should be founded. the possible cause of vibration in pump is due to its structure, weight of the motor placed at higher cause maximum vibration, or improper misalignment between upper and lower base part of pump [11].

2. PROBLEM STATEMENT

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 being completely structural. This entails applying some structural modifications that were done quickly and thoughtlessly. Many trials were done by station experts to reduce the high vibration levels, such as welding braces to the structure. These modifications did not yield any positive 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. Measurements are done for full load and no load operating conditions to confirm the source of the problem if it was from the motor itself or it was from the whole system. Firstly, for no load condition, the connection between the motor and the pump via coupling was separated, then, it is re-connected again for full load condition measurements.

The data collector analyzer is used for measuring and analyzing the recorded vibration signals resulting from the operation. The frequency analysis is carried out to define vibration levels and excitation frequencies, then, evaluate the pump's dynamic running condition. One prod/ ACOEM vibration analyzer and Data collector MVP200 are used for vibration analysis in addition to the Machine Monitoring software package type XPR300 Premium. The signals from the accelerometers are directly fed into the analyzer which possesses an internal signal conditioning system comprising filters, integrator's, amplifiers, etc. The signals are then transferred to the PC via a USB connection to the software for signal analysis. All these measurements were taken according to ISO 10816-3 which determines the status of machines if they are working in good dynamic conditions in accordance with international measurements.

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 motor non-drive end in the radial direction on both sides of the motor.

Measurement locations and 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 dangerous and not allowed to operate the pumping system in this condition, according to ISO 10816 -3 that defines up to 11.2 mm/s is just tolerable level and what exceeds this value is not permissible and dangerous. It was obvious that vibrations during full load are slightly higher than those during no-load at the corresponding locations. The maximum vibration level measured at the full load pump unit increases by about 25%. Operating the pump system at a full load condition generates other sources of unwanted vibration. Connecting the motor to the pump system has little effect on the motor's vibrations. This revealed that the vibration source is from the motor itself, whether the motor is connected 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 excitation forces at these locations. Due to excitation sources of the motor non-drive end bearings, vibration at these locations is usually changing due to the presence of faults and problems at these locations. The operating conditions during such faults increase vibrations and may lead to damage and failure.

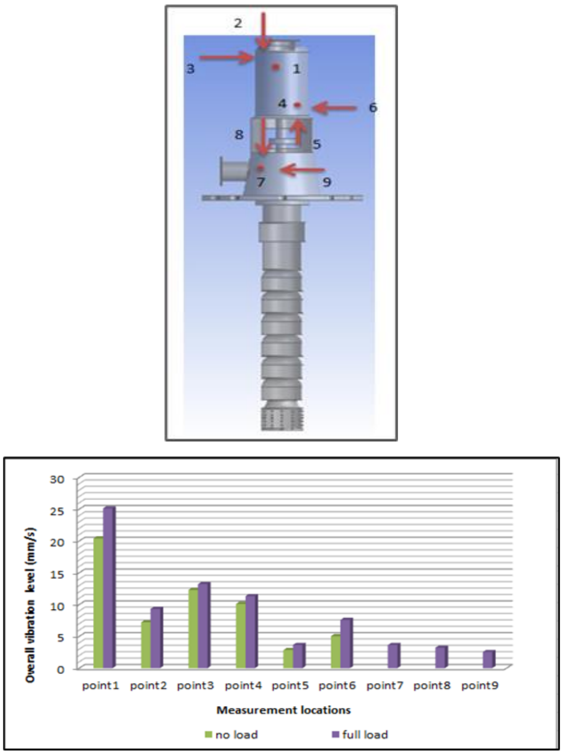

Fig. 1. Measurement locations for vibration levels during no-load and full-load

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 mm/s 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 9.32mm/s at the motor speed. Based on these results, it was obvious that the source of high vibration 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 avoid such undesirable outcomes. The most important first step is to define if the source of the increased vibration is resonance in the rotating machine or the supporting structure.

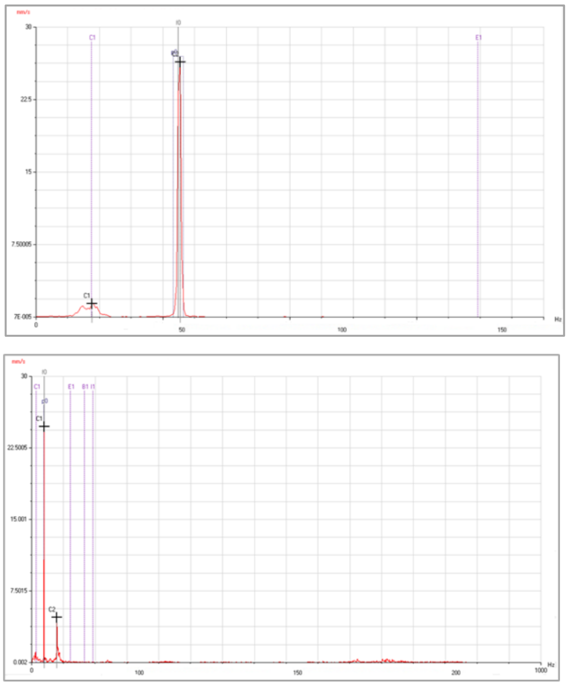

Fig. 2. Vibration spectrum at full load condition in vertical and horizontal directions

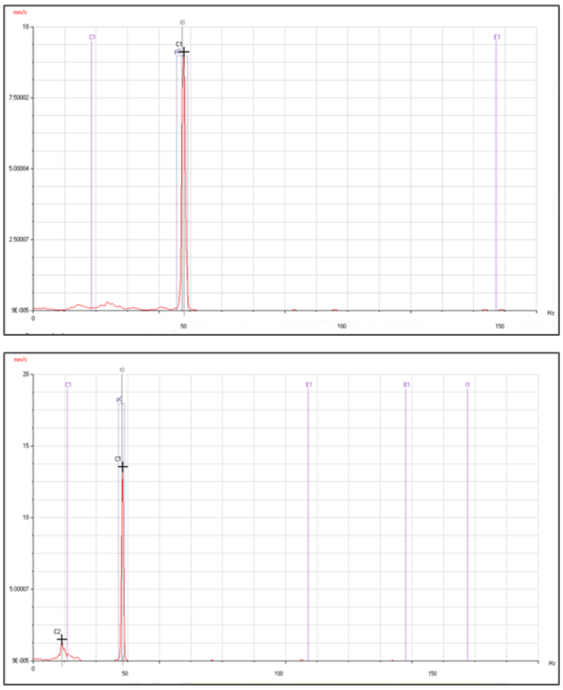

Fig. 3. Vibration spectrum at no load condition in vertical and horizontal directions

Resonant vibration in mechanical structures such as pumps and motors occurs when a natural frequency is at or close to a forcing frequency such as rotor speed. This condition can cause severe vibration levels by amplifying small vibratory forces from machine operation. The solution frequently depends on the ability to distinguish between structural resonance and a rotor critical speed. So, it is very important to determine if the source 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.

3.1. Experimental modal testing analysis

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. The pump must be stopped and hit with an impact hammer that has a soft tip. the pump's natural frequencies are determined according to a response curve. 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 determined as a higher natural frequency from that direction. The other direction which is perpendicular to the pump discharge will usually have a lower industrialist and 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. The test was applied to the motor when it was shut down by using a spectrum analyzer (B&K pulse 3560 hardware module 5 channels), Impact hammer to excite the pump unit with an impulse, accelerometer, and modal analysis software package (Modal Test Consultant Type 7753).

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 within 20% of the allowable operating speed range, any small force could be significantly amplified.

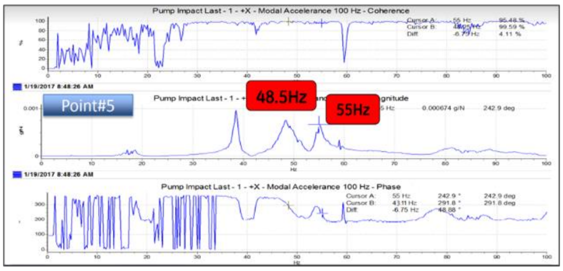

Fig. 4. Impact test results showing main natural frequencies

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.

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 respectively. Vibration amplitudes decreased by about 39% in the vertical direction while they decreased by 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 range of the pump, high vibrations can occur. The next step is to conduct a modal calculation, in this case using a finite element analysis model.

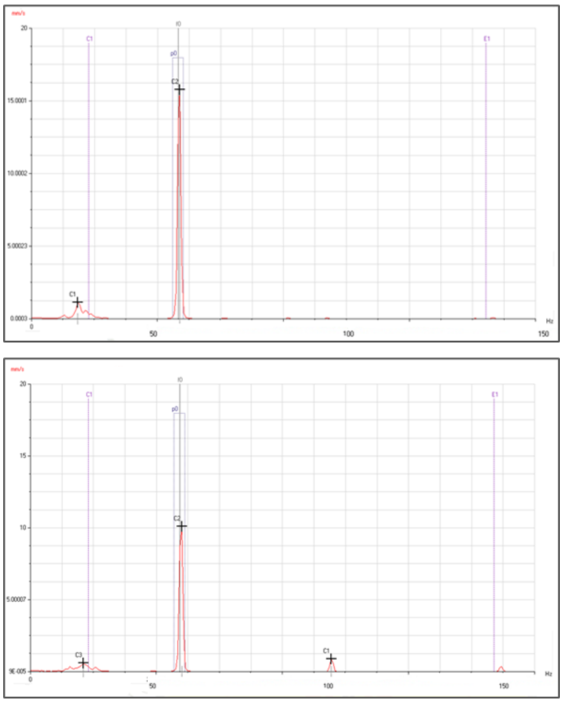

Fig. 5. vibration spectrum measured in the vertical and horizontal directions after applying modifications

3.1. Finite element analysis

Vertical turbine pumping systems are long cantilever-type structures that have mechanical natural frequencies (MNFs) which can occur at pump operating speeds creating resonant vibration conditions. These natural frequencies are also named reed critical frequencies (RCFs) because the mode shape looks like a cantilever model. If the pump motor 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 stage for new pump-motor collections, 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 pump structure resonates at operating speed and hence is subjected to large displacements. As a result, more time and money were needed to be poured in for correcting the design. To avoid such instances, it is necessary to carry out a modal analysis of the pump to determine its dynamic characteristics such as its natural frequencies and corresponding mode shapes. This will limit its vibration amplitudes within the values specified in ISO 10816 [12].

The scope of an RCF Analysis includes the creation of a finite element (FE) model of the motor-pump system. Numerical analysis is carried out by using the FEA tool ANSYS 14.5 to determine the modal 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 motor unbalance from the pump unbalance. 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.

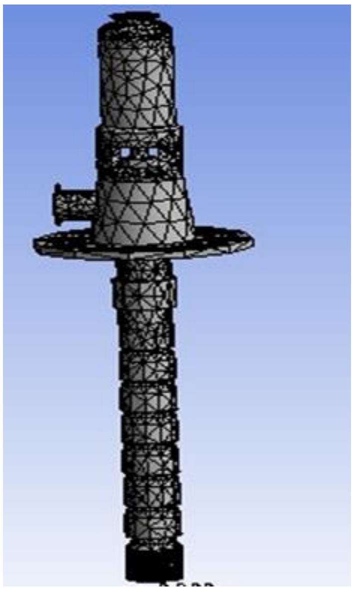

Fig. 6. Mesh model of the pump system

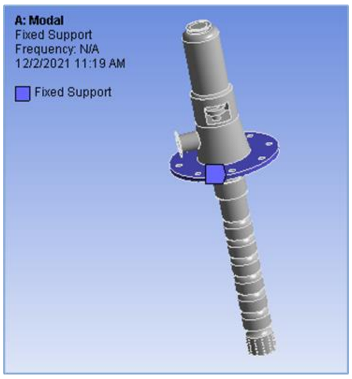

Fig. 7. Model boundary conditions

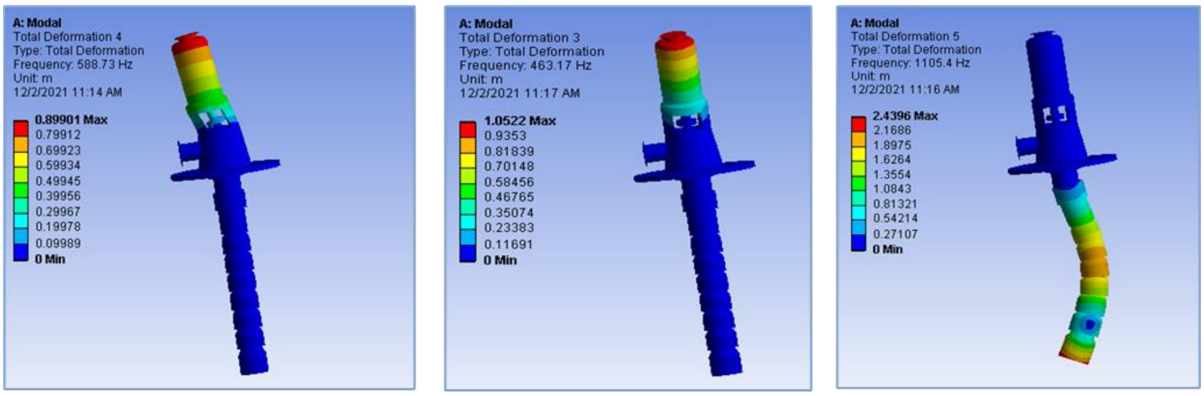

Fig. 8 Mode shapes indicate the circular motion of the model

3.2. Analysis of unbalance problem

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 [13].

In practice, rotors can never be perfectly balanced because of manufacturing errors such as porosity in castings, non-uniform density of material, manufacturing tolerances and gain or loss of material during operation. As a result of mass unbalance, a centrifugal force is generated and must be reacted against by bearing and support structures [14]. Thus, whenever the rotor speed passes through a speed where a rotor with the appropriate unbalance distribution excites a corresponding damped natural frequency, and the output of a properly placed sensor displays a distinct peak in response versus speed, the machine has passed through a critical speed [15].

Mechanical unbalance is the most common cause of machinery vibration. It always produces a force at a machine rotation speed of 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 to 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).

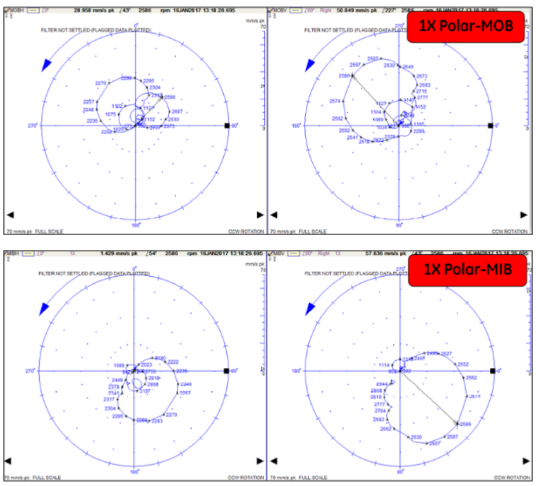

Fig. 9. Polar plot response indicating resonance loop

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 mistake in the balancing procedures applied by a local vendor at the workshop. The balancing shot was done by adding up a total 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 final 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. Vibration amplitude reached 3.22 mm/s and 3.50 mm/s in the radial and axial directions. The vibration level decreased by about 80% in 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.

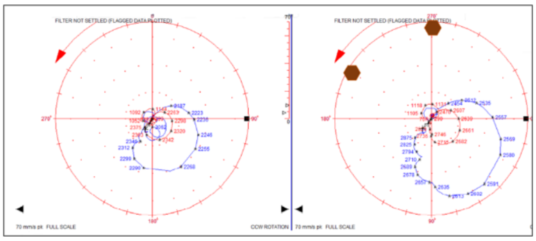

Fig. 10. Polar plots indicated added weights

6. CONCLUSION

- The preliminary analysis results confirmed that the vibration level reached dangerous and unacceptable level of the pumping system.
- Results obtained from experimental modal testing verified the existence of two natural frequencies.
- Modifications are carried out through increased mass by adding a specific weight to the structure.
- After applying modifications, vibration levels decreased by about 48% in the vertical direction, however, they decreased by about 39% in the horizontal direction.
- Although applying these modifications, the vibration level was still high and not permissible, particularly in the motor.
- Results indicated that all modes were away from the operating speed.
- On-site motor balancing was implemented to eliminate the excitation forces which resulted in good findings.
- The vibration level decreased by about 80% in the vertical direction and 66% in the horizontal direction after solving the problem.
- Precise measurements and analysis helped to discover and accurately identify the problem. This undoubtedly leads to faster repair of problems and a reduction in downtime.

Declaration of competing interest: *The author declares no conflict of interest.*

REFERENCES

1. Ahobal N, Ajit Prasad SL. Study of vibration characteristics of unbalanced overhanging rotor. IOP Conference Series: Materials Science and Engineering, International Conference on Advances in Materials and Manufacturing Applications (IConAMMA-2018) 2019;577. https://dx.doi.org/10.1088/1757-899X/577/1/012140.
2. Larsen JS, Santos IF. On the nonlinear steady-state response of rigid rotors supported by airfoil bearings-theory and experiments. Journal of Sound and Vibration 2015;346:284-297. https://doi.org/10.1016/j.jsv.2015.02.017.
3. Tchomeni BX, Alugongo A. Numerical and experimental diagnosis of complex rotor system by time-frequency techniques. MATEC Web of Conferences 2018;169:01015. https://doi.org/10.1051/matecconf/201816901015.
4. Birajdar R, Keste A. Prediction of flow-induced vibrations in vertical turbine pumps using one-way fluid-structure interaction. The 14th International Conference on Vibration Engineering and Technology of Machinery (VETOMAC XIV) 2018; 211. https://doi.org/10.1051/matecconf/201821116002.
5. Xu C, Zhai J, Zhang H, Han Q. Simulation study on unbalance vibration characteristics of dual rotor system. SN Applied Sciences 2020; 2(1423). https://doi.org/10.1007/s42452-020-03237-5.
6. Birajdar R, Keste A. Prediction of flow induced vibrations due to impeller hydraulic unbalance in vertical turbine pumps using one way fluid−structure interaction. Journal of Vibration Engineering & Technologies 2020;8:417–430. https://doi.org/10.1007/s42417-019-00174-5.
7. Kiliç R. Determination of imbalance problem in electric motor and centrifugal pump by vibration analysis. Special issue of the 2nd International Conference on Computational and Experimental Science and Engineering 2016; 130(1): 487-491. http://dx.doi.org/10.12693/APhysPolA.130.487.
8. Birajdar RS, Keste AA, Gawande SH. Critical hydraulic eccentricity estimation in vertical turbine pump impeller to control vibration. Hindawi International Journal of Rotating Machinery; Volume 2021. https://doi.org/10.1155/2021/6643282.
9. El- Gazzar D. Finite element analysis for structural modification and control resonance of a vertical pump. Alexandria Engineering Journal 2017, 56(4): 695–707. https://doi.org/10.1016/j.aej.2017.02.018
10. Nikumbe AY, Tamboli VG, Wagh HS. Modal analysis of vertical turbine pump. International Advanced Research Journal of Science, Engineering and Technology 2015;2(5). http://dx.doi.org/10.17148/IARJSET.2015.2525.
11. Prajapati H. Vibration in vertical centrifugal pump. IJARIIE. 2016;2(6).
12. Kumatkar RR, Panchwadkar AA. Modal analysis of rotor assembly of vertical turbine pump. International Engineering Research Journal (IERJ) 2015; 2: 325-333.
13. Sen A, Majumder MC, Mukhopadhyay S, Biswas RK. Polar and orbit plot analysis for unbalance identification in a rotating system. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) 2017; 14(3): 49-56. http://dx.doi.org/10.9790/1684-1403054956.
14. Saleem A, Diwakar G, Satyanarayana M. Detection of unbalance in rotating machines using shaft deflection measurement during its operation. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) 2012;3(3):8-20. http://dx.doi.org/10.9790/1684-0330820.
15. Swanson E, Powell C, Weissman S. A practical review of rotating machinery critical speeds and modes. Journal of Sound and Vibration 2005; 39(5): 10–17.

Received 2022-11-03
Accepted 2023-05-12
Available online 2023-05-13

Dalia Mohamed EL- GAZZAR
Affiliation: mechanical and electrical research institute, national water research center, ministry of irrigation.
Degree: assistant researcher
Telephone: (02) 42189884
Mobile: 01011718619
E-mail: daliam4@yahoo.com