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Experimental Investigation and Finite Element Analysis for Solving Pumps Resonance Problem

Sami A. A. El-Shaikh
Mechanical & Electrical Research Institute,
National Water Research Center, Ministry of Water Resources & Irrigation,
Delta Barrage, Egypt

Abstract:- **Resonance problem leads to failure and damage for pumping stations. In this research, vibration problem in Helwan Irrigation Pump Station is studied and analyzed to define and control vibration sources due to resonance problem leading to breakdown and failure of the concrete foundation for most pumps in the station.**

A finite element model of the pump station was built defining the stresses on the various parts of the motor and foundations affecting the structure. Vibration level was measured and frequency analysis was done on the pump parts and on the foundations. A high (dangerous) level of vibration measured is16.4 mm/sec. Frequency analysis shows that there is a resonance problem. The model suggests different scenarios to solve the structural problem. Applying the different scenarios and measurements are repeated until the problem disappeared where the level of vibration is in the range of 3.9 mm/sec (allowable).

It was found that the level of vibration measured is serious (16.4 mm/sec) at the motor non drive end (MNDE) in the horizontal direction. Frequency analysis showed that there is resonance problem. The model suggested different scenarios to solve the structural problem and overcome the resonance by adding supports to the motor foundation. Applying the structure modification scenarios from the model results helped in the reduction of the vibration level by 80% and solving the resonance problem.

The results point out that adding definite supports to wakened motor foundation at the sensitive nodes modifies the structural characteristics, enhance the dynamic behavior, and keep the pumping stations in smooth running conditions avoiding the resonance associated problems.

Keywords: ***Pump vibration; support weakness; dynamic performance***

I. INTRODUCTION

Vibration is one of the most serious problems in the pumping stations in Egypt. Pumping stations, especially vertical pumps, are sensitive to mechanical and structural problems leading to vibrations. **As noted by Swarup (1989)**, resonance problem must be prevented to avoid these high levels of vibrations for vertical pumps as vertical and inclined installations of these pumping systems introduce vibration problems of such plants.

Resonance phenomena constitute the most serious problem of vibration, where the operational forces excite one or more of the natural frequencies. So, it is very important to determine the modal parameters (modal frequency, modal damping, and mode shape) to give a complete dynamic description of the structure and form a mathematical dynamic model **(Bruel & Kjaer (1988).**

Sinha and Rama (2005) conducted modal analysis on the complete assembly of pumps, piping layout and identified resonance as the root cause for pump failure.

DeMatteo (2001) proved that modal techniques are powerful tools that enhance an analyst's ability to understand the sources of vibration. A case history of vertical pump was investigated. Testing progression from problem identification in route vibration measurements to resonance testing was presented. Resonance problems are difficult to solve. . Modal Analysis give a clear picture of the machine’s motion, however neither tool has the capability to solve resonance problems.

Scheffer (2008) conducted an experiment to monitor pump condition through vibration analysis. Vibration from their sources may be small but excite the resonant frequencies of the rotating parts such as the rotor shaft and set-up considerable extra dynamic load on bearings. **Simmons (1992)** argues that the cause and effect reinforce each other and the machine progresses towards ultimate break down.

The pump base plate is the interface between the casing feet and the foundation. The baseplate and foundation are often a key factor in establishing the so-called “reed” frequencies of a pump, the vibration motion that particularly vertical pumps often exhibit near running speed. **William and Marscher (2014)** indicated that this factor in the installation and qualification of new pumps is often overlooked by civil engineers and mechanical contractors when they design and construct a new or revised pump installation. **(Marenco G, Nicchio A and Pivo A. (2009)** studied and proved the effect of the base plate stiffness on improving the dynamic characteristics of the pump assembly.

Frequency plays a large role in vibration related structural damage. Common structures have a low natural frequency, typically less than 30 Hz. Structural vibration is exponentially increased if the vibration frequency falls within the bounds of the natural frequency of the structure. This phenomenon is commonly known as resonance. Thus, low frequency vibrations are potentially more of a concern than their high frequency counterparts. **Department of the Army and Airforce (1995)** ensured that the possibility of superficial damage is minimized a vibration criteria of 5 mm/sec has been recommended. For very old structures, an even lower level of 1.25 mm/s is recommended. On the other hand, RGBS (1995) concluded that a 0.07 g (acceleration of gravity) vibration is recommended as a safe limit of large structures.

Doebling (1996) presented a comprehensive literature review of damage identification and health monitoring methods for structural and mechanical systems focusing on methods based on vibration measurements and detection based on changes in vibration characteristics.

It can be concluded from the review that the pump system is complicated as it includes different structures and sources of vibration. Resonance constitutes the most serious problem of the pumping stations. Old buildings and heavy foundations of the pumping housings are affected by the problem and are subjected to breakdown and failure. Resonance problem must be determined and solved analytically and experimentally. Diagnosis of the machine parts must be evaluated based on vibration velocity, where structure falure based on vibration acceleration parameter.

II. PROBLEM STATEMENT

Helwan Irrigation Pump Station consists of 8 pump units and located inside Helwan drainage pumping station to lifting of water to Saf canal for irrigation purposes. Map for location of Helwan Irrigation Pump Station is shown in **Figure (1)**. Each pump unit is of 1500 L/sec discharge, 39.5 m head; 745 rpm pump speed, 900 kW motor power, and 8500 kg motor weight. Equipment that used for test/measurement is one proD/ACOEM vibration analyzer and Data collector MVP200 serial 11141 with Machine monitoring SW type XPR300 Premium.

Existing foundation has low stiffness because it consists of smaller size and numbers of beams than the beams were designed by the manufacturer. Also, the existing foundation has bad supporting at the connection between it and the pump base. This low foundation stiffness and bad supporting are the main cause of the motor vibration.

Deviation from the pumps manufacture design and construction specifications for the motor base would usually cause many problems including the increase of motor vibration levels. The following are typical examples of such deviations:

- The use of support steel beam which is smaller than recommended in addition to the inappropriate positions/numbers of stiffeners and supporting plates for the motor base **Figure (2)**. This would normally result in weak supporting positions for the motor base.
- The bolts that connect the pump base and the foundation are not integrated properly, as shown in **Figure (3)**.
- Improper fixation of the motor soleplates due to missing or lose bolts. In **Figure (4)**, the motor three soleplates were fixed from two sides instead of four as recommended by the standards design.

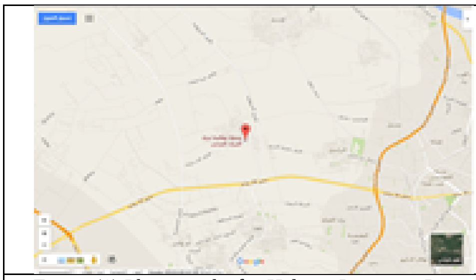

Figure (1) Photographs for Helwan Irrigation Pump Station location

Figure (2-a) Stiffeners and Supporting Plates

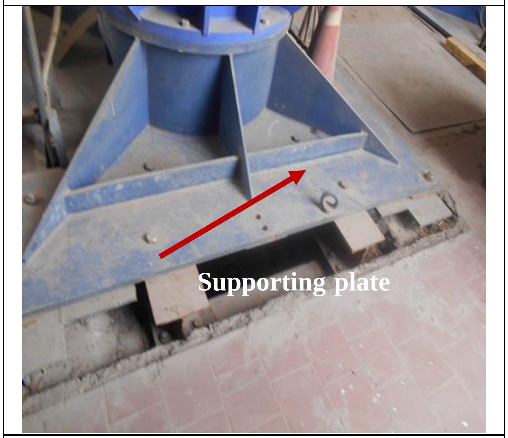

Figure (2-b) Stiffeners and Supporting Plates

Figure (3) Bolts

These problems in the existing foundation have contributed to the pump vibration, foundation and its old base plate is as shown in **Figure (4)**.

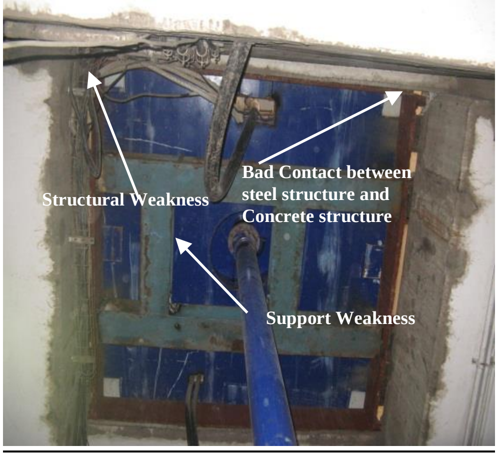

Figure (4) Old base plate

III. RESEARCH METHODOLOGY

The objective of this research is to solve resonance problems based on vibration measurement and finite element analysis results. Optimum structural changes and sensitive nodes are well defined for modifying the system dynamic behavior. The recommendations of the model results were applied to the structure to overcome resonance problem and strengthen the foundation weakness. Vibration measurements were repeated after modifications showing that smooth and safe vibration level. The following steps are done:

- Measuring overall vibration level at nine locations on all units in three perpendicular directions to indicate the severity of vibration to assess the status of machinery in accordance to the manufacture standards.
- Doing frequency Analysis to: identify high unwanted frequencies for each element in the pump system;define the exciting frequencies and determine the level of vibration at each specific frequency.
- Performing a finite element analysis (FEA) using COMSOL ver 5.1 (a finite element analysis, solver and Simulation software / FEA Software package for various physics and engineering applications) to study the difference between the existing and design foundations.
- Generating the mode shapes of existing model for the pump assembly
- Applying the results on the actual model in the field until the pump station is dynamically safe.
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IV. RESEARCH METHODOLOGY

Overall vibration analyses were done by measuring vibration in three perpendicular directions on all units of Helwan Irrigation Pump Station to specify the sources of vibration and to define the exciting frequencies due to running conditions. All measurements were taken with root mean square velocity (RMS) in a frequency range from 2 Hz to 1 kHz and the results were compared with the standard. Simple spectrum vibration velocity Fast Fourier Transform (FFT) in a frequency range from 2 Hz to 1 kHz was done for diagnosis pump mechanical problems and simple spectrum vibration acceleration was taken from10 Hz to 10 kHz for diagnosis high frequency problems (mechanical). The measurement locations are determined on the parts of the pump at nine locations. The overall vibration level measurements for one unit are listed in **Table [1]**.

Overall vibration level was measured and the results were analyzed. Results of measurements show that the vibration level is higher than the standards, as shown in **Table [1]**.

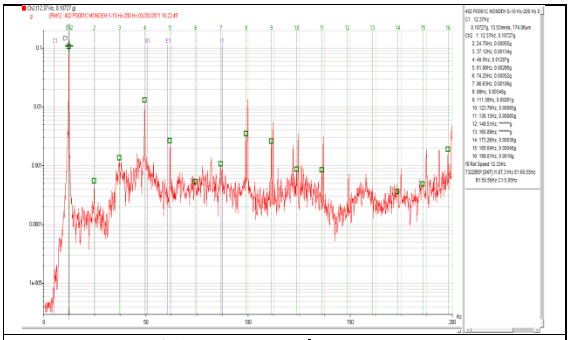
Table [1] Overall vibration velocity level measured (mm/sec)

Location Measurements	Reference Data (Before Modification)
Motor None Drive End Horizontal (MNDEH)	16.41
Motor None Drive End Vertical (MNDEV)	4.21
Motor None Drive End Axial (MNDEA)	2.62
Motor Drive End Horizontal (MDEH)	4.43
Motor Drive End Vertical (MDEV)	2.11
Motor Drive End Axial (MDEA)	2.74
Foundation H	4.9
Foundation V	3.21
Foundation A	2.49

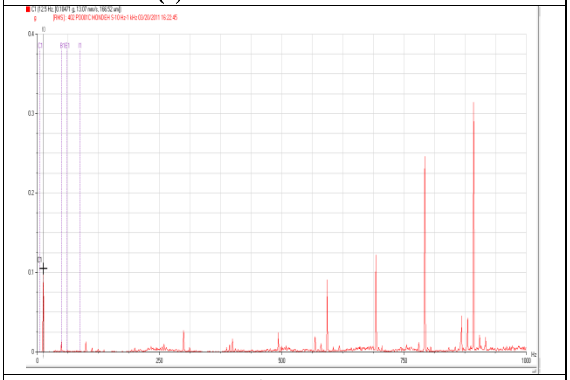
According to the ISO 10816-3standards for machines with power greater than 300 kW, the desired level of vibration, (RMS velocity level) is up to 2.3 mm/sec; with the allowable level until 4.5 mm/sec, and a restricted operation level up to 7.1 mm/sec. The results of measurements **(Table [1])** indicated that there are severe high vibration levels on the motor which is higher than the standards, where the level of vibration reached in one case up to 16.4 mm/sec which was more than double the restricted operation levels. The other pump units had the same problem and each one was solved solely as it takes time and effort to measure and apply recommended structural modifications on steps to achieve required dynamic behavior and response.

Frequency analysis was done to determine high frequencies unwanted, frequencies for each element in the pump system, and to know problem at any frequencies. Frequency spectrum analysis indicated that there were vibration peaks at motor running speed (1X ≈ (12.4Hz) and its harmonics in the vertical and horizontal directions. It is obviously noticed that the maximum vibration amplitude reached 13.5 mm/sec at 12.5 Hz as shown in **Figure (5-a)**, its harmonics as shown in **Figure (5-b)**, and peaks with high amplitude at low frequency as shown in **Figure (5-c)**. These high levels of vibration are in the “not permissible zone" of ISO 10816-3 indicating a resonance problem. It is not safe and dangerous to operate at this condition. Normally weakness in foundation causes this observed resonance problems.

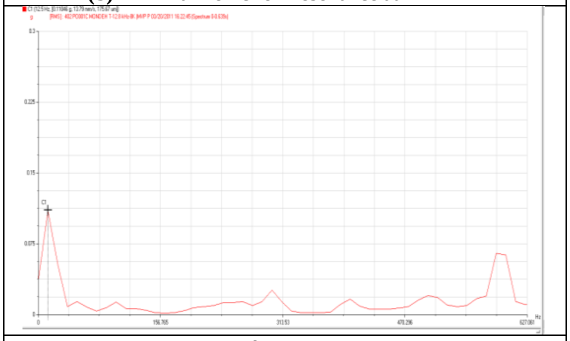
From results and analyses for the manufacturer design, the existing foundation, and mode shapes of original model, it's found that the existing foundation has low stiffness because it consists of smaller size and number of beams than the beams were designed by the manufacturer. Also, the existing foundation has bad supporting at the connection between it and the pump base. This low foundation stiffness and bad supporting are the main cause of the motor vibration.



(a) FFT Domain for MNDEH



(b) FFT Harmonic for Resonance at MNDEH



(b) FFT Harmonic for Resonance at MNDEH

Figure (5) Frequency Analysis (before modification

Proper maintenance work was carried out by the user to improve the pump concrete foundation to provide good fixation for motor soleplates. Work included: the fixation for the pump discharge gab, **Figure (6-a);** increase fixation at the base of the pump, (**Figure (6-b)** and modification of the foundation as shown in **Figure (7)**. Finally, dynamic analysis was done after increasing supports for the foundation.

(a) There is no fixation for the pump discharge gab distance 6 mm

(b) Weak fixation. The base of the pump should be 1.5 the width of the feet

Figure (6) Increasing concrete modification

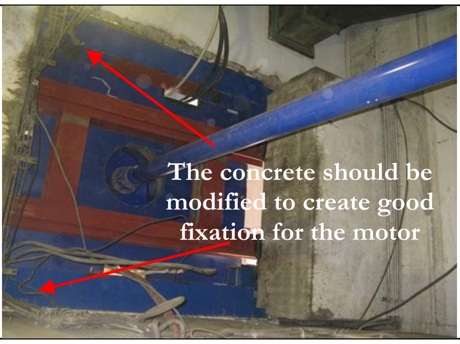
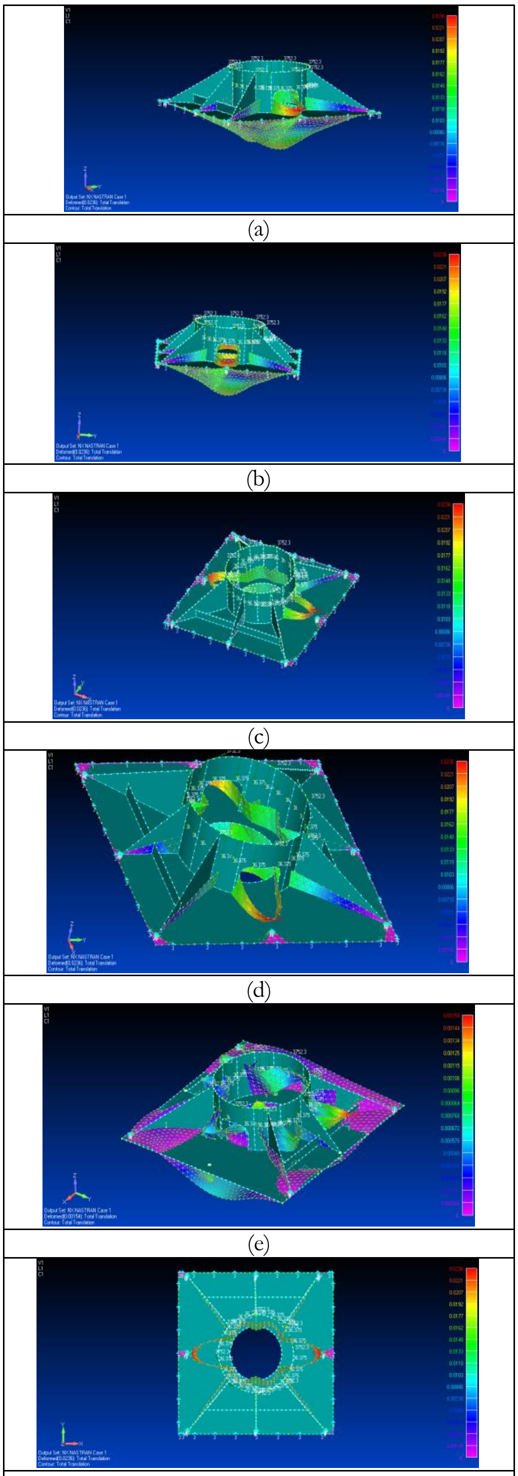


Figure (7) The concrete should be modified to create good fixation for the motor soleplates in both sides

V. FINITE ELEMENT ANALYSIS

A finite element analysis was performed by COMSOL Software Ver. 5.1 to study the difference between the existing foundation and the foundation that was designed by the manufacturer. The foundation that was designed by the manufacturer was as shown in **Figure (8)**.

The finite element analysis for the manufacturer base design indicates that the maximum deformation occurs at the middle of the base where there is no support for the base. On the other hand this design provides a rigid supporting for all sides of the base.



(a)

(b)

(c)

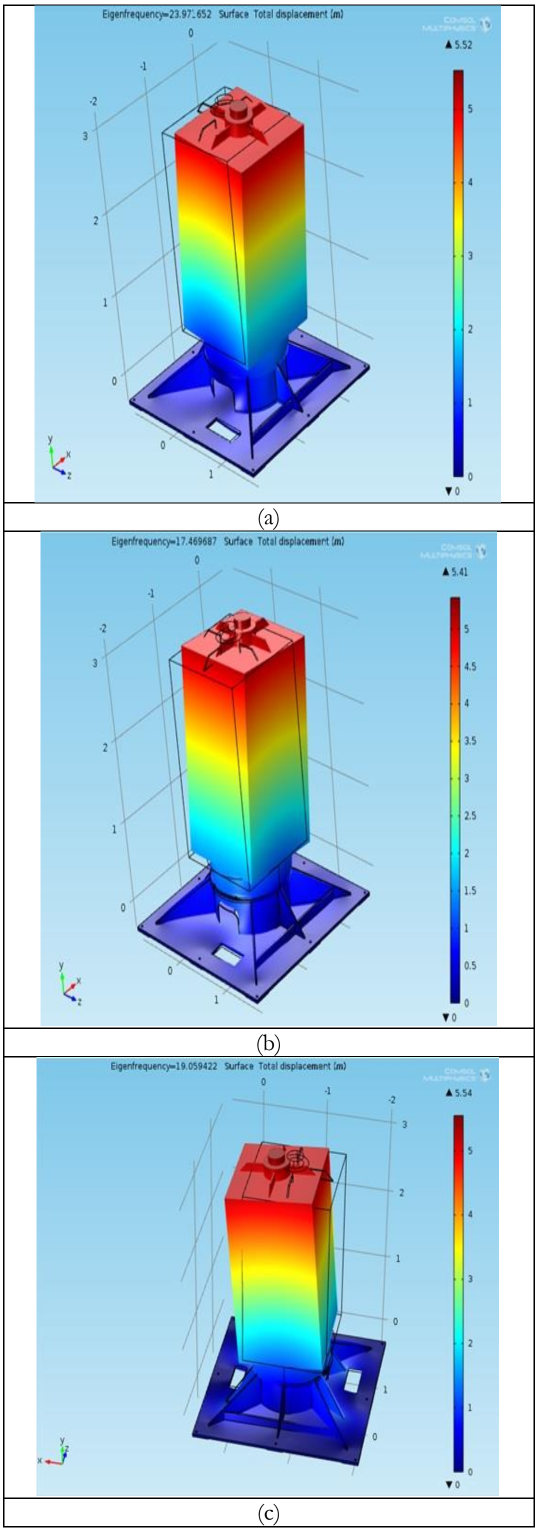
(d)

(e)

(f)

Figure (8) Different views for the foundation that was designed by the manufacturer

The mode shapes analysis of original model that was done by COMSOL Software. Figure (9) the six scenarios done to reach the best design with no stresses on the various parts of the motor and foundations affecting the structure, no deflection, operating smooth with safe vibration level. The mode shapes analysis of original model that was done by COMSOL Software. **Figure (9)** the six scenarios done to reach the best design with no stresses on the various parts of the motor and foundations affecting the structure, no deflection, operating smooth with safe vibration level.

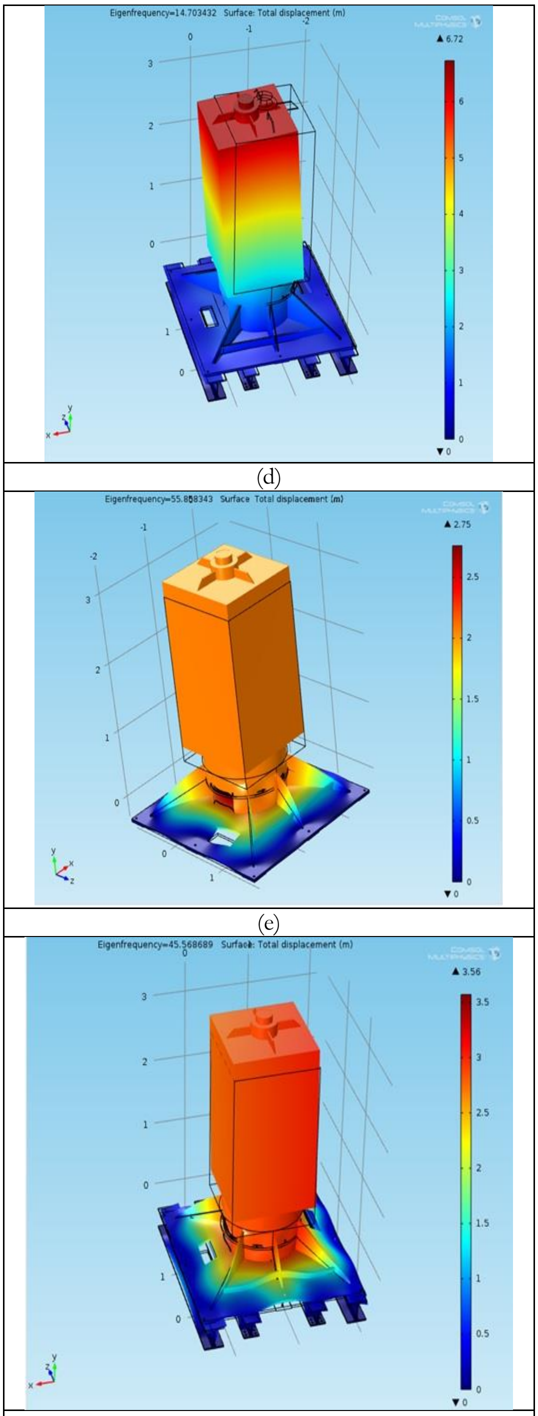


(a)

(b)

(c)

There is no fixation for the pump discharge gab distance 6 mm



(d)

(e)

(f)

Figure (9) Modal analysis with COMSOL software Ver. 5.1 for motor and foundation

The existing foundation provides cross beams which decreased the base middle deformations and stresses. On the other side, the base side supports are very weak and this kind of supporting participated in the existing pump vibration.

From results and analyses for the manufacturer design, the existing foundation, and mode shapes of original model, it's found that the existing foundation has low stiffness because it consists of smaller size and number of beams than the beams were designed by the manufacturer. Also, the existing foundation has bad supporting at the connection between it and the pump base. This low foundation stiffness and bad supporting are the main cause of the motor vibration.

So, the user must have to follow the foundation design recommended by the manufacturer, as shown in **Table [2]** for dimensions and in **Figure (10)** for adding stiffeners. Complete description and dimension for this design will be prepared. The new design will increase the foundation stiffness by adding two cross beams at the middle of the manufacturer foundation as described in the figure below, as shown in **Figure (10)**. The new base should be fixed properly from four sides.

Table [2] Dimensions of two foundation beams (mm)

	Depth	Width	Web thickness	Flange thickness	Fillet radius
HEB 320	**240**	240	10	17	21
HEB 240	**320**	300	11.5	20.5	27

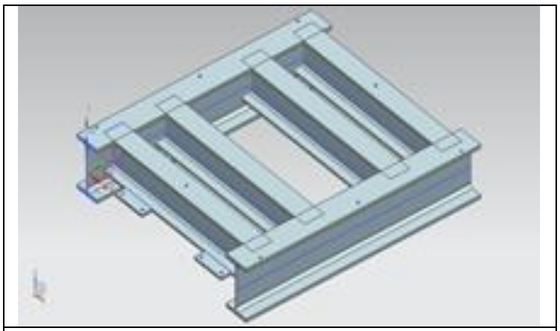
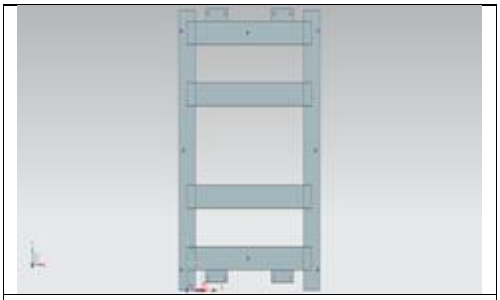


Figure (10) The manufacturer foundation that was designed

Analytical modal analysis of the pump was carried out for the quick identification of natural frequencies and the mode shapes for the pump assembly. COMSOL Software Ver 5.1 The pump was analyzed without considering the piping connections and the motor coupling because their influence in this analysis is negligible. Also Solid Work Program was used to draw this pumping station to represent the problem in theory. **Figure (11)** illustrates the assembly of the foundation, while **Figure (12)** illustrates the assembly of the motor, motor base, and foundation.



(a)

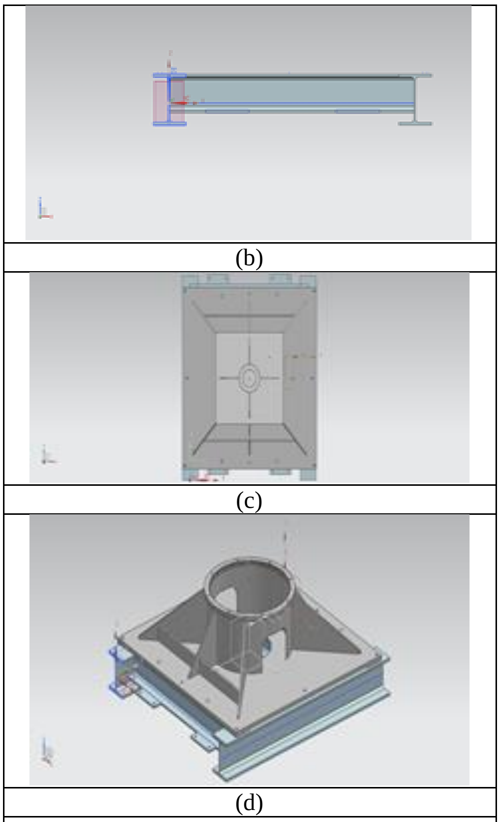

(b)
(c)
(d)

Figure (11) Different views for the foundation

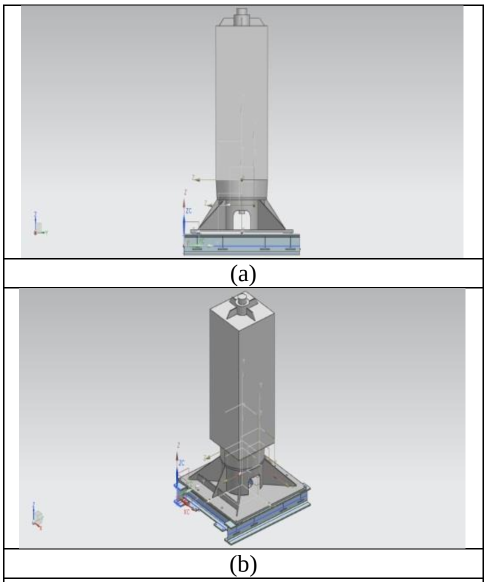

(a)
(b)

Figure (12) Foundation modification showing the motor, motor base, and foundation

VI. EXPERIMENTAL RESULTS AFTER STRUCTURE MODIFICATIONS

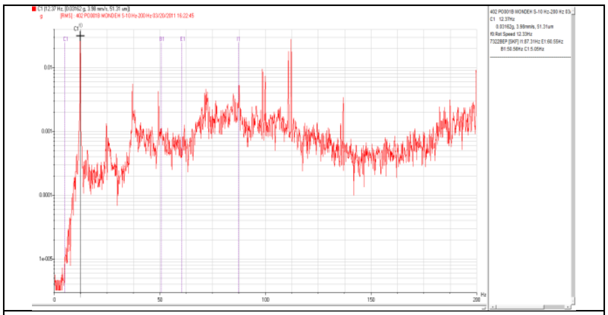
Dynamic Analysis is done after applying the modification for the foundation.

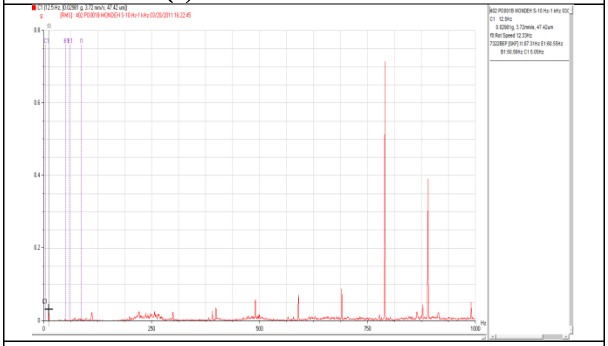
Overall vibration level was re-measured after model modification and the results were analyzed. The measurements results indicating that the resonance problem was disappeared and solved. The level of overall vibration was in the range of 3.9 mm/sec. The level of vibration improved with almost about 80%, decrease, as shown in Table [3]. This level is acceptable according to ISO Standard.

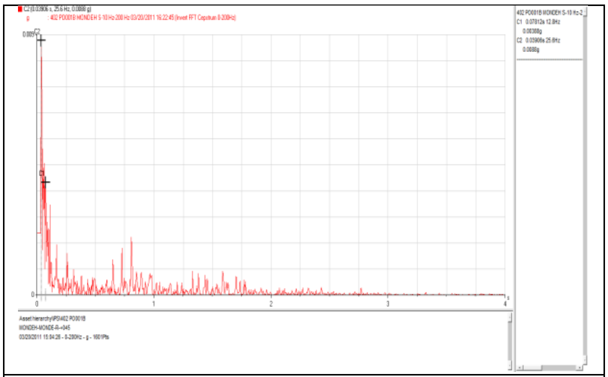
Table [3] Overall vibration velocity level measured (mm/sec)

Location Measurements	Before Modifications	After Modifications
Motor None Drive End Horizontal (MNDEH)	**16.4081**	**3.91899**
Motor None Drive End Vertical (MNDEV)	**4.2**	**1.83127**
Motor None Drive End Axial (MNDEA)	**2.61675**	**1.57005**
Motor Drive End Horizontal (MDEH)	**4.42803**	**1.72365**
Motor Drive End Vertical (MDEV)	**2.105983**	**0.74102**
Motor Drive End Axial (MDEA)	**2.73915**	**1.64349**
Foundation H	**4.9**	**1.94339**
Foundation V	**3.2038**	**0.92858**
Foundation A	**2.4857**	**1.49142**

Frequency spectrum analysis indicated that no vibration peaks were found at motor running speed (1RPM, 12.5Hz, reached to 3.98 mm/sec, as shown in **Figure (13-a)**, no harmonics as shown in **Figure (13-b)**, and no peaks with high amplitude at low frequency as shown in **Figure (13-c)**.


(a) FFT Domain for MNDEH


(b) FFT Harmonic for Resonance at MNDEH



(c) Time domain for Peak at low frequency at MNDEH

Figure (12) Foundation modification showing the motor, motor base, and foundation

VII. CONCLUSIONS

The baseplate and foundation are often a key factor in the installation and qualification of new pumps that often overlooked by civil engineers and mechanical contractors when they design and construct a new or revised pump installation. Field investigation and a finite element analysis revealed that the difference between the existing foundation and the manufacturer designed one is the root cause of the observed high vibration levels. The low foundation stiffness and bad supporting were the main deviation items in the pump installed foundation. The vibration analysis of the motor indicates severe looseness problem where the base of the motor need to be fixed properly and also indicates unbalance problem. The blade passing frequency of the pump generates high vibration and excites the natural frequency for the pump. The pump bearings are also in a bad condition (cage passing frequency for the bearings). High vibration levels were measured at 1x running speed of the motor due to resonance problem. The run-up tests confirmed a natural frequency at 16.5 Hz, which coincides with the motor running speed. The results of finite element analysis confirmed that the third natural frequency was very close to 1x operating speed with deviation about 1%. The resonance problem solved by increasing the machine stiffness at the lower motor base where the motor vibration level decreased by 80%. The results point out that adding definite supports to the weak motor foundation at the sensitive nodes modifying the structural characteristics, would enhance the dynamic behavior, and keeping the pumping station units in smooth running conditions.

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