European Journal of Mechanical Engineering Research

Vol.3, No.3, pp.1-17, August 2016

Published by European Centre for Research Training and Development UK (www.eajournals.org)

DIAGNOSIS OF PUMP PROBLEMS USING VIBRATION ANALYSIS

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ABSTRACT: *Pump stations are generally exposed to various problems which affect efficiency, performance, reliability, operating life of the pumps, and maintenance cost. Vibration in pumps may be a result of improper installation, lack of maintenance, weak foundation, resonance and etc. Axial flow pumping system is usually used to deliver high discharges at low heads. Vertical and inclined installations of these pumping systems cause structural vibration problems for such plants. Axial Flow Pumping stations always have long rotating shafts working as a cantilever fixed at the bottom (pump) and free at the top (motor). The objective of this research is to identify the causes of the high vibration of El-Marashda (1) pumping station due to weakness of the foundation. Effect of adding steel to supports motor foundation is studied to overcome structural weakness of the vertical pump support. Vibration level was measured and frequency analysis was also done on the pumps parts and on the foundations by adding steel supports gradually at different conditions to determine the source of vibration and the path of vibration transmission to the foundation. From initial measurements, vibration levels measured on all units are in the danger level. Different case studies are evaluated at different conditions experimentally to obtain the optimum dynamic conditions. Adding steel supports to motor foundation at two stages gradually fixed the problem and reduced the high vibration level.* ***Firstly,*** *adding steel supports to motor foundation reduced the velocity vibration level* ***53%****, reduced the acceleration vibration level* ***24%****, and reduced the bearing defect factor (BDF)* ***22%****.* ***Finally,*** *increasing steel supports to motor foundation reduced the velocity vibration level* ***91%****, reduced the acceleration vibration level* ***91%****, and reduced the BDF* ***56%****. The dynamic characteristics of the pump structure have improved and the measured vibration level is safe. Vertical pump foundation should be carefully designed and strengthened to resist the dynamic loads. Inspection and regular maintenance is important to avoid any abnormal conditions leading to dynamic loads affecting both pump components and foundation.*

KEYWORDS: Pump Vibration, Dynamic Performance.

INTRODUCTION

Pumping stations are subjected to many problems affecting performance, efficiency, and maintenance cost. Pumps subjected to operational forces generated by their operating speed, system head, pressure and piping arrangement. “Detecting pump problems using vibration analysis includes cavitation, pump flow pulsation, bent pump shaft, shaft misalignment, pump bearing problems, and unbalance of pump impeller”(**technicalassociates 2014).**

High vibration level causes damage to the structure of the housing building and foundations of the pumping stations. **Smalley (1994)** presented a method for assessing the severity of vibration in terms of the probability of damage by analysis of vibration and its related cost. Damage due to vibration costs millions of dollars for maintenance and replacement expenses. Vibration condition monitoring as an aid to fault diagnosis of rotary machines has been used

ISSN 2055-6551(Print), ISSN 2055-656X (Online)

successfully since more than 30 years. **Yoon (2013**) indicated that The American Petroleum Institute (API) defines the critical speed to be the rotational speed of the shaft that causes the rotor/bearing/support system to operate in a state of resonance. In other words, the frequency of the periodic excitation forces generated by the rotor operating at the critical speed coincides with the natural frequency of the rotor/bearing/support system.

Daniel (2013) ensured that vibration analysis is the cornerstone of all pump performance monitoring programs. Vibration level of a pump is directly related to where it is operating and in relation to its Best Efficiency Point (BEP). Further away from the BEP, the higher the vibrations will be. There is no absolute vibration amplitude.

As noted by **William D. Marscher (2014),** the pump baseplate is the interface between the casing feet and the foundation. A baseplate and the foundation have some degree of flexibility, and therefore they are major contributing factors in the overall stiffness through which the mass of the pump is grounded mechanically to the earth. The baseplate and foundation are, therefore, considered often a key factor in establishing the so-called “reed” frequencies of a pump. Reed is the vibration motion that particularly vertical pumps often exhibit near running speed.

EBARA (1997) and **JAAEE (1991) indicated that** the causes of pump vibration are broadly divided into three groups: excessive vibrating force, low rigidity, and resonance. Excessive vibrating forces are due to hydraulic and mechanical factors. Hydraulic factors include cavitation, surging, clogging of vane passage, and breakage of vanes due to entrance of foreign matter. Mechanical factors include imbalance of rotating components, defective shaft coupling due to misalignment, improper installation, and pipe loads imposed due to poor support of suction and discharge pipes. Low rigidity, other cause, of pump vibration is due to low strength of components including casing, and low foundation strength due to weak foundations or improper tightening of foundation bolts. Resonance or self-excited oscillation is mainly due to:

- Pressure pulsation in the pump coincides with the natural frequency of casing or piping,
- Vortex formed near the suction pipe, and
- Speed corresponding to natural frequency of the rotating component.

Simplified models are cantilevered beams with a mass at the end to represent a single stage end-suction pump, and a simply supported beam on an elastic foundation. A good reference for these and other models have been presented in the handbook by **Blevins, R. (1984)**. The following is an example of how to apply these formulas for the case of the effects of imbalance on a single stage end pump with the impeller cantilevered relative to the bearings. The lowest natural frequency (the “reed” mode) in cycles per minute could be represented by the the following equation:

$$f_{nl} = \left({}^{60}\!\Big/_{2\pi[{}^{(3EI)}\!/_{\{L^3(M+0.49M_S)\}}]^{1/2}} \right)$$

$f_{nl} =$ Lowest natural frequency

$EI =$ Young's modulus of elasticity

$L =$ Shaft length and moment of inertia

$M =$ Impeller mass

$M_S =$ Mass of the shaft

If the eccentricity of the impeller relative to the bearing rotational centerline is, and the rotational speed is rad/s, then the unbalance force is simply:

$$F_{ub} = {M_e \omega^2}\big/{g_c}$$

$F_{ub} =$ Unbalance Force

$\omega =$ Rotational speed

$M_e =$ Impeller mass eccentricity

$g_c =$ Gravitational speed

and the amount of vibration displacement expected at the impeller wearing rings is:

$$\delta = \left(F_{ub} * L^3\right)\big/\left(3EI\right)$$

PROBLEM STATEMENT AND METHODOLOGY

In this study, mechanical problems of Marashda (1) Pumping Station are assessed. Marashda (1) Pumping Station was constructed in 1994 to serve an irrigation area of 500 feddans in Nagaa Hamadi Area in Upper Egypt. It consists of 5 pump units as shown in **Figure** (1). Each pump unit is of discharge 2.2 m^3/sec, head 12 m, pump speed 598 rpm, motor power 456 kW, motor speed 1483 rpm, and gearbox ratio 62/25 (2.48), number of drive Gear teeth is 25, number of driven Gear teeth is 62, and rated output power is 430 KW. Vibration Severity Criteria, **(ISO 10816) 1995**, is shown in **Figure (3)** for velocity. Results of acceleration were compared with Reservoir and Grand Barrage Sector Standard, RGBS (2005) shown in **Table (1)**. Frequency analysis was done at low and high frequency to define the exciting frequencies and determine the level of vibration at each specific frequency, to determine the sources of vibration, to control vibration levels, and to solve vibration problems. Then, measurements were repeated twice after maintenance and adding supports to motor foundation with load and no load conditions to fix the high vibration level problem.

Figure (1) Photograph for Marashda

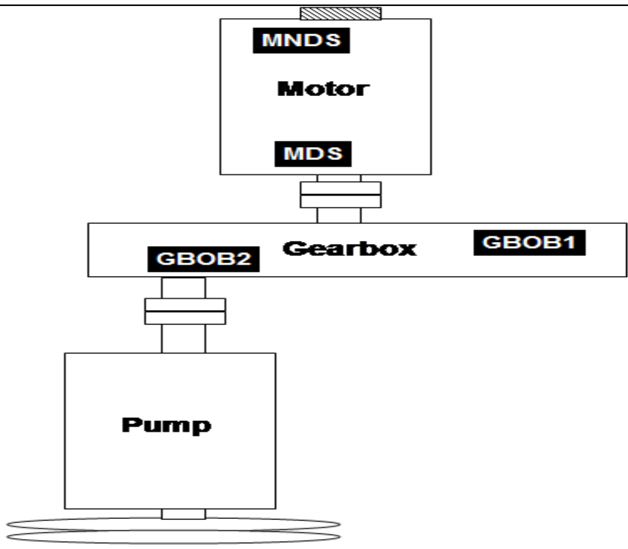

Figure (2) Measurement locations

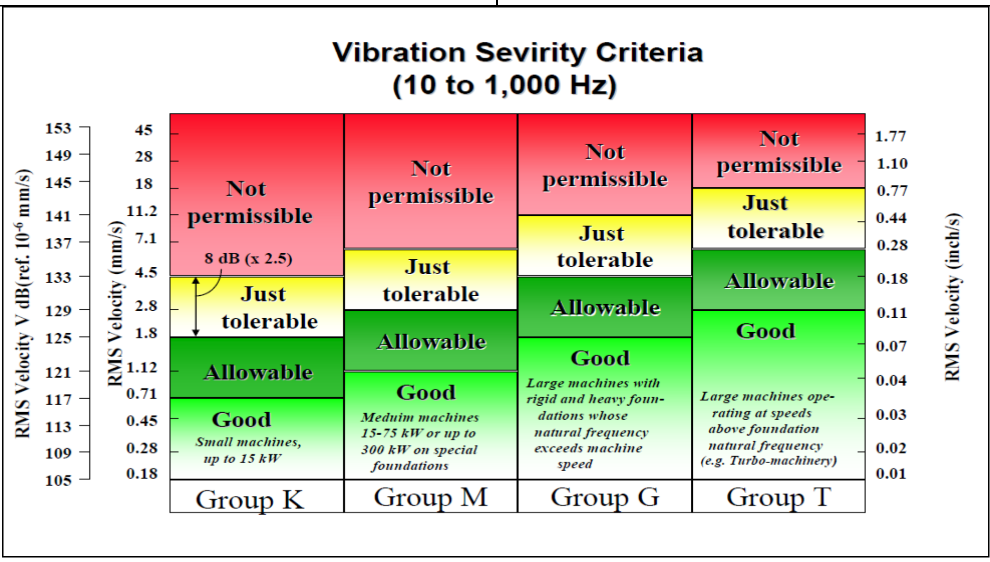

Figure (3) ISO standard for vibration

Table [1] limits for gravity vibration acceleration: Reservoir and Grand Barrage Sector Standard, RGBS (2005)

Machine condition	Acceleration (g)	Bearing Defect Factor (BDF)
Acceptable	Level less than 1 g	Level less than 6
Alarm	level higher than 1 g and less than 1.5 g	Level less than 1 g and higher than 9 g
Danger	Level higher than 1.5 g	Level less than 9

ISSN 2055-6551(Print), ISSN 2055-656X (Online)

RESULTS AND ANALYSIS OF VIBRATION MEASUREMENTS

Firstly, *overall vibration* levels in terms of root mean square, rms vibration velocity, gravity vibration acceleration, and bearing defect factor were measured and analyzed at *load* and *no load* conditions. **Secondly** maintenance and fixation of the problems were done and measurements were repeated. **Then** dynamic analyses were carried out at all conditions to determine seriousness and causes of the problems. **Lastly;** dynamic analysis indicated disappearance of the problem.

Case (1): results for initial measurements at full load

Overall vibration levels that were measured *with load* for the five pumping unit's show that the level of vibration in terms of vibration velocity, gravity vibration acceleration, and bearing defect factor for all units were in the danger level, as shown in **Tables [2**, **3**, and **4]**.

From initial measurements and analyses it was found that overall vibration velocity level for motor non drive end (MNDS) is in danger level where level is reached to 17.6 mm/sec at (H), and the level is reached to 4.8 mm/sec at (V). While, the gearbox overall vibration levels at GBOB1V and GBOB2V are in alarm level where levels are reached to 6.21 mm/sec and 6.01 mm/sec receptively.

Also, from measurements and analyses, the overall vibration acceleration level for motor are within the acceptable range and in the alarm level for all measurements except at the MNDV is in danger where level is reached to 1.59 g. Also, the gearbox overall vibration levels are in danger level at all measurements especially on the GBOB2H where the level is reached to 15.5 g.

From measurements and analyses, the levels of bearing defect factor BDF are within the acceptable range except at the gearbox is in the alarm level, as shown in **Table [2]**.

Table [2]: Overall vibration velocity levels (mm/s) for five units with full load ***(initial measurements)***

Measurement Locations	Pump 1	Pump 2	Pump 3	Pump 4	Pump 5
MNDSH	**17.6**	**7.17**	3.02	**5.22**	**5.583**
MNDSV	**4.8**	3.59	2.97	12.6	0.597
MNDSA	1.2	1.48	1.32	3.04	0.569
MDSH	1.5	0.656	0.396	0.987	0.197
MDSV	0.597	1.06	0.479	1.09	0.238
MDSA	1.4	2.87	1.31	1.98	0.353
GBOB1H	3.12	3.17	1.86	3.38	2.13
GBOB1V	**6.21**	4.38	1.24	4.65	1.96
GBOB1A	2.32	1.96	1.32	1.92	1.13
GBOB2H	3.18	2.6	2.42	2.89	1.56
GBOB2V	**6.01**	3.19	1.2	3.87	1.8
GBOB2A	0.877	0.791	0.776	0.8	0.623

Also, from measurements and analyses, the overall vibration acceleration level for motor are within the acceptable range and in the alarm level for all measurements except

ISSN 2055-6551(Print), ISSN 2055-656X (Online)

at the MNDV is in danger where level is reached to 1.59 g. Also, the gearbox overall vibration levels are in danger level at all measurements especially on the GBOB2H where the level is reached to 15.5 g, as shown in **Table [3]**.

Table [3]: Overall vibration acceleration levels (g) for five units with full load ***(initial measurements)***

Measurement Locations	Pump 1	Pump 2	Pump 3	Pump 4	Pump 5
MNDSH	1.42	1.32	1.26	1.35	1.47
MNDSV	1.18	1.02	1.18	1.37	0.933
MNDSA	1.06	**2.02**	1.31	**1.66**	0.932
MDSH	1.23	1.31	1.32	1.49	0.9
MDSV	**1.59**	**2.27**	**1.95**	**2.34**	1.24
MDSA	0.703	**1.95**	1.16	1.24	1.07
GBOB1H	**2.72**	**1.8**	**3.85**	**2.61**	**4.16**
GBOB1V	**3.47**	**2.7**	**2.55**	**2.13**	**3.38**
GBOB1A	**8.1**	**1.71**	**2.42**	**2.39**	**3.8**
GBOB2H	**15.5**	**6.18**	**12.5**	**6.21**	**6.51**
GBOB2V	**5.79**	**6.08**	**7.07**	**5.96**	**4.07**
GBOB2A	**3.41**	**1.81**	**2.84**	**2.17**	**2.18**

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From measurements and analyses, the levels of bearing defect factor BDF are within the acceptable range except at the gearbox is in the alarm level, as shown in **Table [4]**.

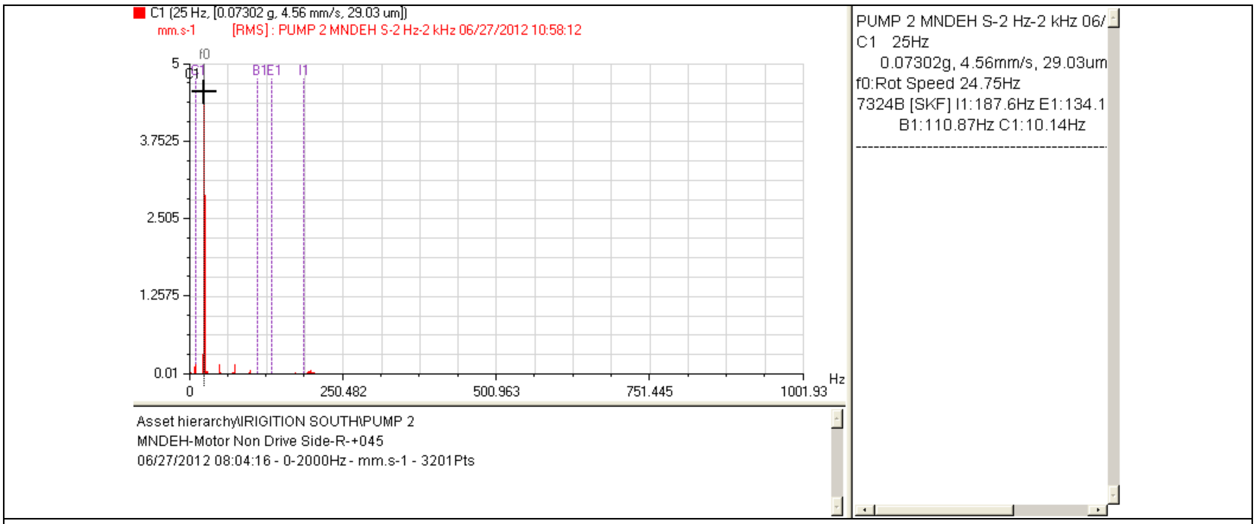
Table [4]: Overall vibration Bearing Defect Factor (BDF) for five units with full load ***(initial measurements)***

Measurement Locations	Pump 1	Pump 2	Pump 3	Pump 4	Pump 5
MNDSH	4.88	5.11	5.47	7.33	3.43
MNDSV	3.96	4.32	4.59	**6.62**	3.95
MNDSA	4.26	5.35	4.31	4.07	3.71
MDSH	5.12	**6.34**	**6.49**	**6.92**	4.32
MDSV	4.53	**8.1**	**6.1**	**7.47**	5.41
MDSA	5.94	**8.04**	4.97	5.88	4.22
GBOB1H	5.52	3.99	**6.14**	4.98	**6.19**
GBOB1V	5.86	5.55	5.8	5.19	**6.06**
GBOB1A	**7.72**	5.34	5.21	5.19	**6.46**
GBOB2H	**8.82**	**7.34**	**8.79**	**7.2**	**7.71**
GBOB2V	**7.43**	**7.02**	**7.96**	**7.38**	**6.72**
GBOB2A	5.61	4.31	5.64	4.33	4.57

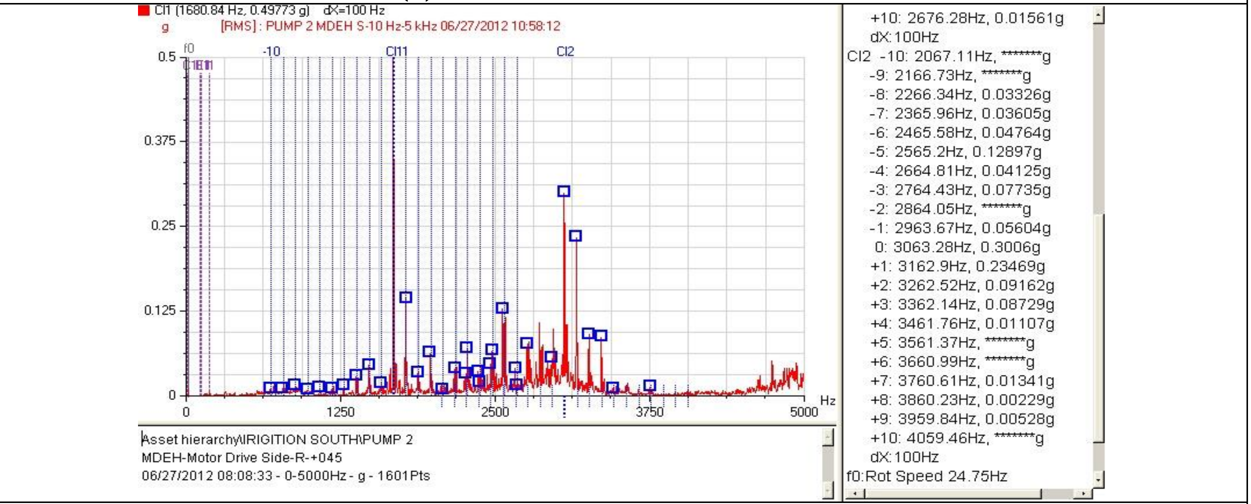
Frequency analysis was done at low and high frequency to define the exciting frequencies and determine the level of vibration at each specific frequency, to determine the sources of vibration, to control vibration levels, and to solve vibration problems. Results of frequency analysis showed that there is motor unbalance problem as shown in **Figures (4-a,** and **4-b)**. Also, the gearbox vibration measurement at motor side showed a problem in the gear teeth caused by misalignment as shown in **Figures (4-c** and **4-d)**. Also, the gearbox vibration

ISSN 2055-6551(Print), ISSN 2055-656X (Online)

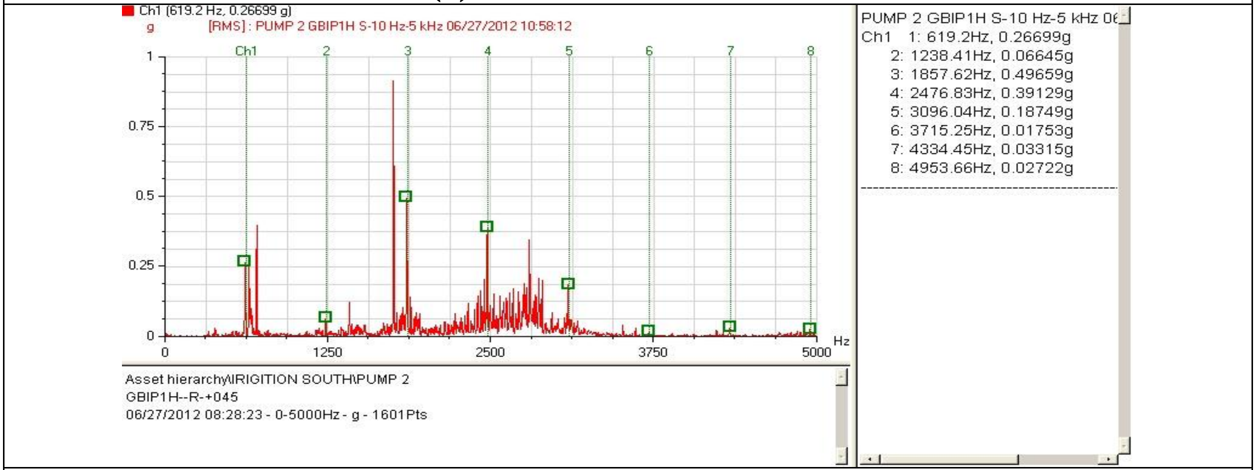
measurement at pump side showed a looseness problem in the gears as shown in **Figures (4-e,** and **4-f)**



(a) motor non drive side horizontal



(b) motor drive side horizontal



(c) Gear Box motor side horizontal

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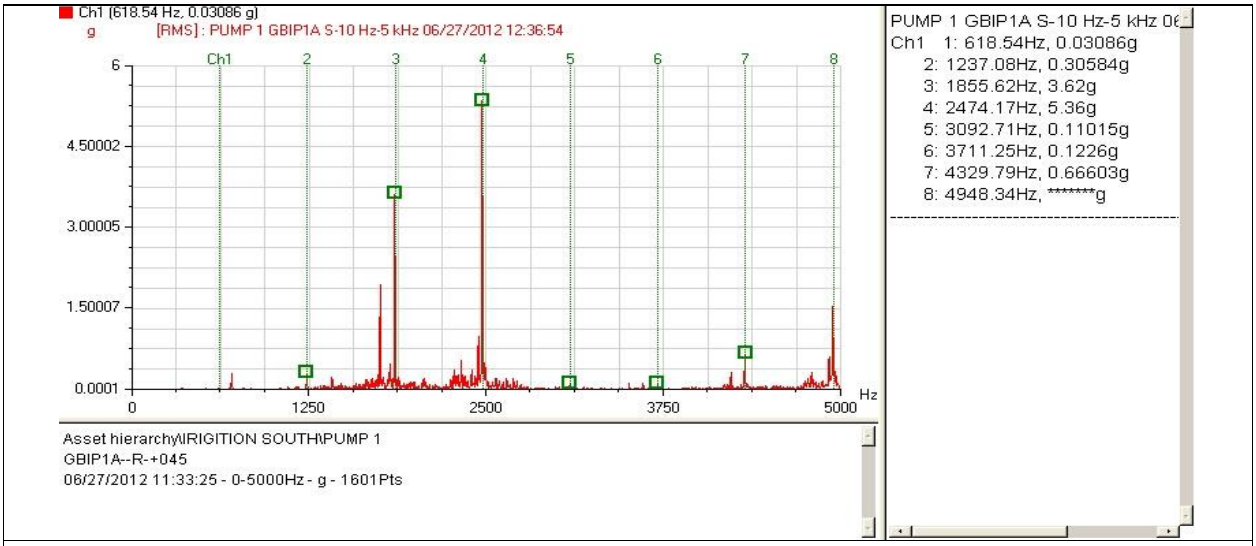
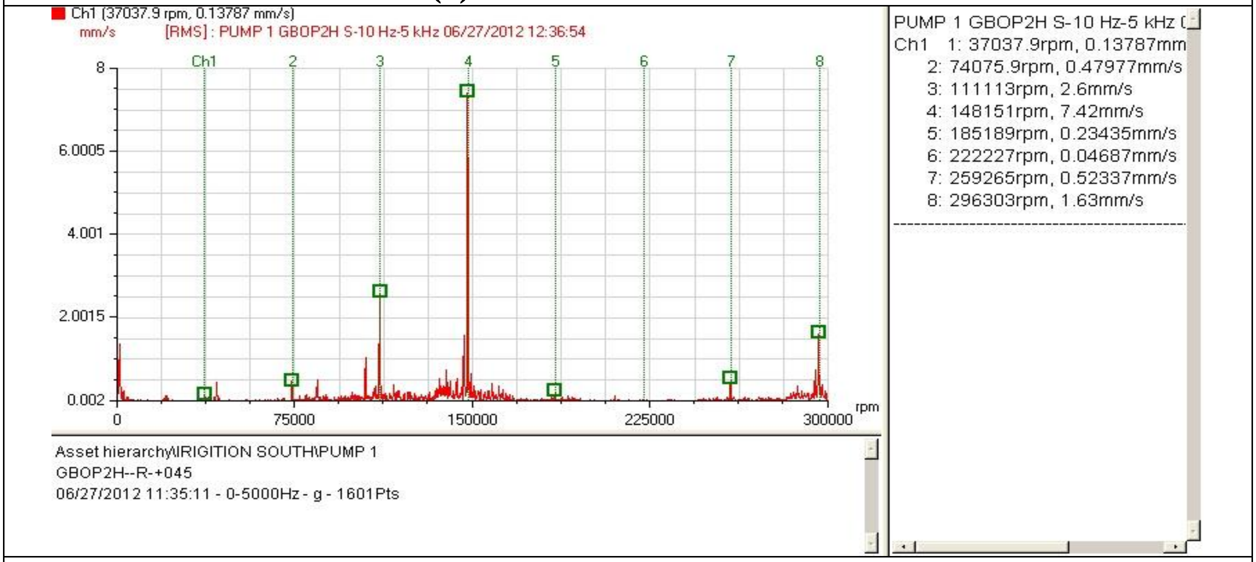
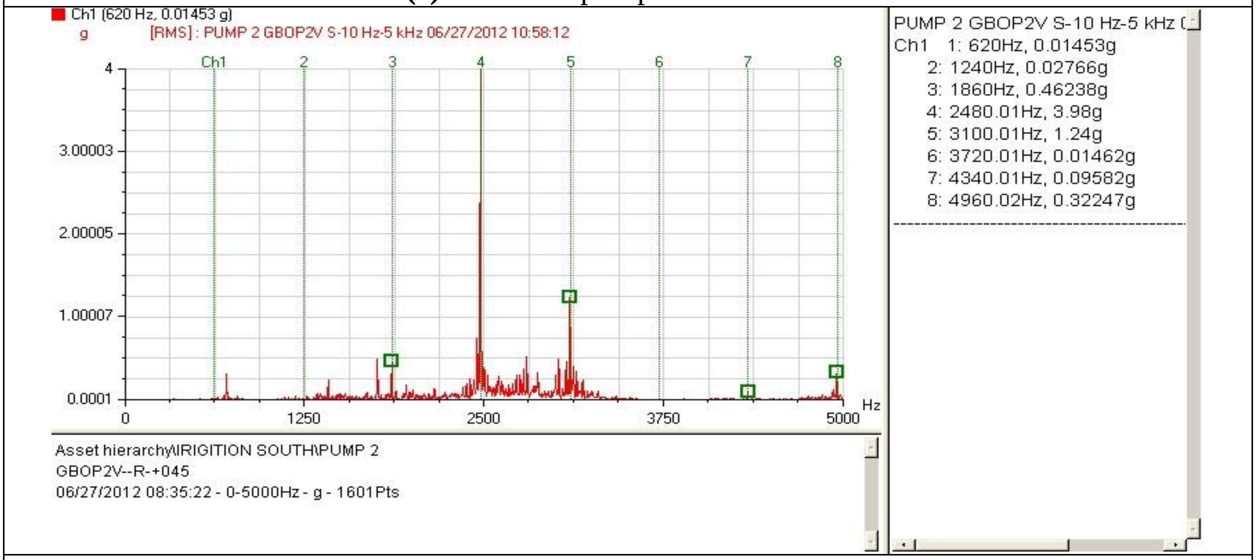


(d) Gear Box motor side Axial



(e) Gear Box pump side horizontal



(f) Gear Box pump side vertical

Fig. (4) Frequency analyses at full load on the motor and gearbox

Case (2): results for initial measurements at no load

Results and analyses for overall vibration and frequency analyses with full load showed that high level of vibration exceeded the danger level. So, measurements were done for one unit with no load (pump 1), as shown in **Table [5]** and then frequency analysis was done.

Table [5]: Overall vibration levels for pump (1) at no load

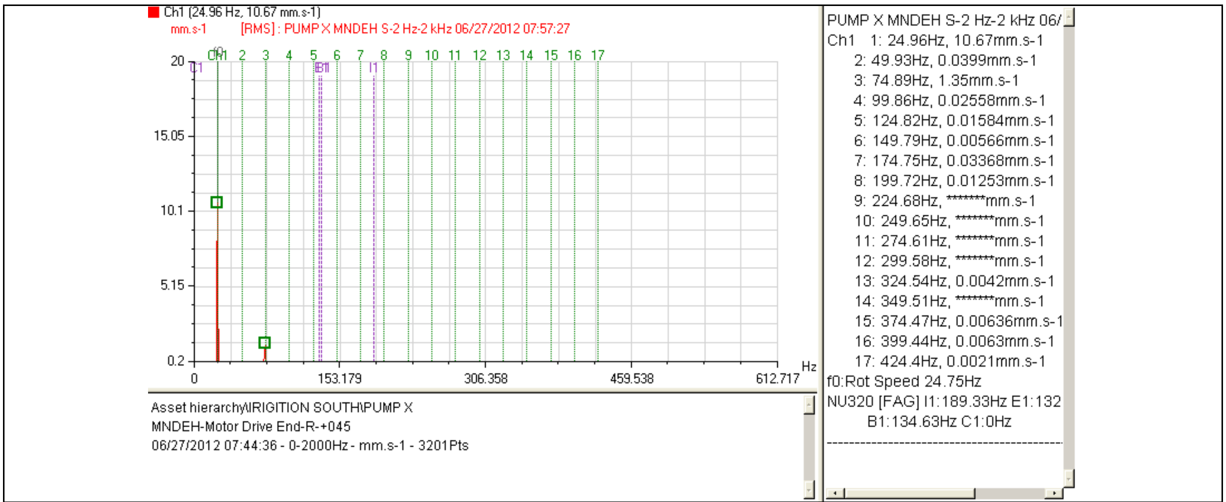
Measurement Locations	Overall Velocity (mm/s)		Overall Acceleration (g's)		Overall Bearing Defect Factor (BDF)	
	Load	No Load	Load	No Load	Load	No Load
MNDSH	17.60	16.30	01.42	01.32	04.88	05.11
MNDSV	04.80	05.10	01.18	01.02	03.96	04.32
MNDSA	01.20	01.48	01.06	02.02	04.26	05.35
MDSH	01.50	01.12	01.23	01.31	05.12	06.34
MDSV	0.597	01.06	01.59	02.27	04.53	08.10
MDSA	01.40	02.87	0.703	01.95	05.94	08.04

From measurements and analyses, the velocity overall vibration level for motor non drive end at no load are within the acceptable range except the motor non drive side horizontal (MNDSH) and at the motor non drive side vertical (MNDSV) is in danger and alarm level where, it reached to 16.3 mm/sec, 5.1 mm/sec respectively as_acceleration shown in **Table [5]**.

Also, from measurements and analyses, overall vibration acceleration level for all measurements for the motor are in the alarm and danger levels where the smallest level is 1.02 g's and highest level is 2.27 g's, as shown in **Table [5]**.

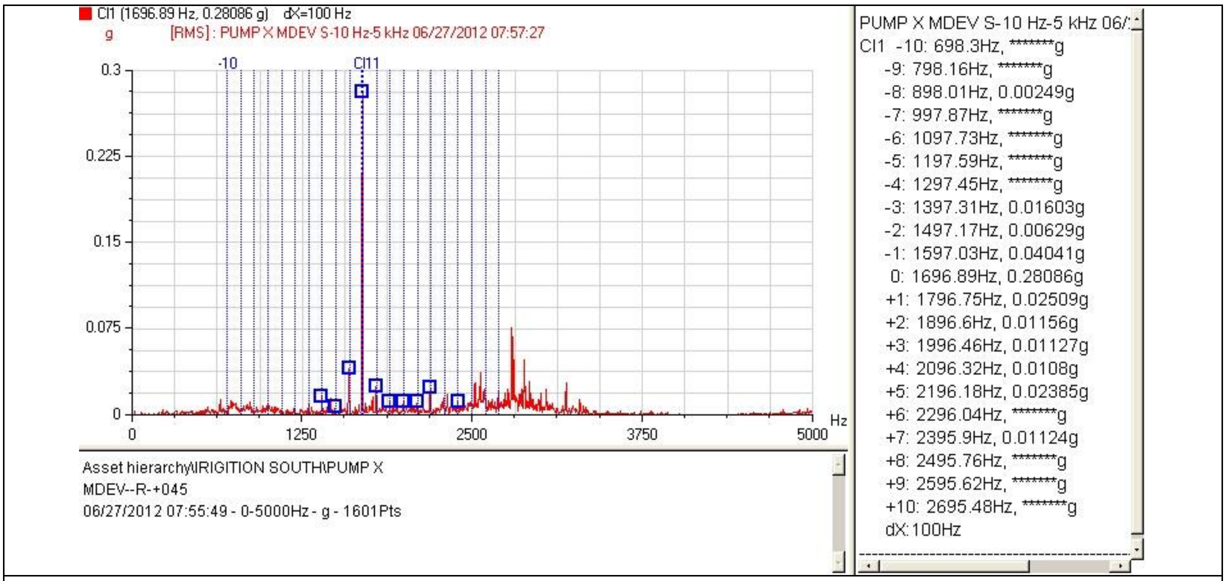
From measurements and analyses, the levels of BDF are within the alarm levels range, where, the level is reached to 8.1 as shown in **Table [5]**.

Results of frequency analyses that were done at the motor show that the motor misalignment problem and resonance problems could be caused by weight of the electric motor, as shown in **Figures (5-a,** and **5-b)**.



(a) : motor non drive side horizontal **MNDSH**

ISSN 2055-6551(Print), ISSN 2055-656X (Online)



(b) : motor drive side vertical **MNDSV**

Fig. (5) Frequency analyses at no load on the motor

RESULTS AND DISCUSSIONS AFTER ADDING STEEL SUPPORTS

The first step was to add steel supports to the motor foundation in addition to doing overall maintenance. Measurements were taken for the overall vibration velocity, gravity acceleration, and bearing defect factor (BDF) at full load, as shown in **Table (6)**.

Case 3: results and discussions after adding steel supports for pump (1) at full load

Overall vibration velocity, gravity acceleration, and BDF at full load were done after adding steel supports to motor foundation, as shown in **Table (6)**. Form velocity measurements and analyses it was found that improvement for all overall vibration levels while some overall vibration levels were still danger as level reached up to 8.13 mm/sec at MNDSH. While, the gearbox overall vibration levels were within the acceptable range except for measurement at the locationsGBOB1V and GBOB2V which were still in the alarm levels the levels reached up to 6.35 mm/sec and 5.71 mm/sec receptively.

While, from gravity acceleration measurements and analyses, and adding steel supports to motor foundation some improvement took place for all overall vibration levels, but some overall vibration levels were still in the alarm and danger level where most measurements are higher than 1 g's as shown in **Table [6]**. Where, overall vibration acceleration is reached to 11.66 g at the GBOB2H.

Also, it's found that improvement for all levels of BDF, but it's still high and in the alarm levels at the gearbox. Where, it reached to 6.66, 6.88, and 6.11 at GBOB1A, GBOB2H, and GBOB2V receptively.

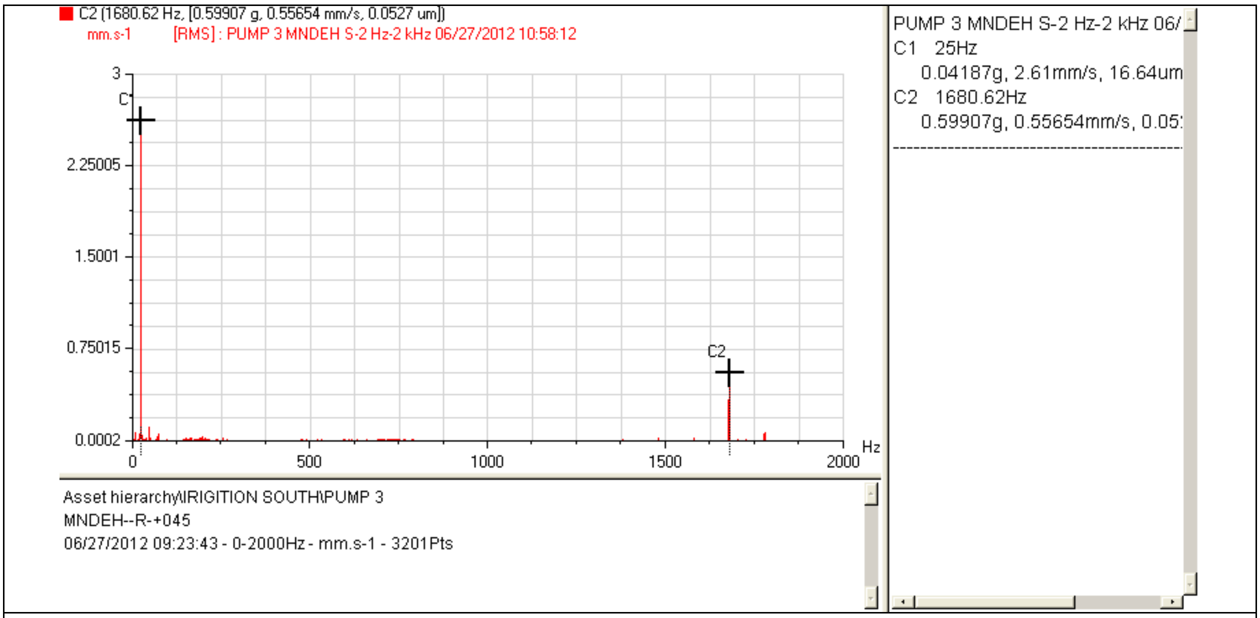
ISSN 2055-6551(Print), ISSN 2055-656X (Online)

Table [6]: Overall vibration levels measured before and after adding steel supports [with full load]

Measurement Locations	Overall Velocity (mm/s)		Overall Acceleration (g's)		Overall Bearing Defect Factor (BDF)	
	Initial measurements	Adding supports	Initial measurements	Adding supports	Initial measurements	Adding supports
MNDSH	17.60	08.13	01.42	00.88	04.88	03.19
MNDSV	04.80	03.06	01.18	00.95	03.96	03.71
MNDSA	01.20	01.41	01.06	00.99	04.26	03.91
MDSH	01.50	01.09	01.23	01.19	05.12	04.58
MDSV	0.597	0.043	01.59	01.44	04.53	04.95
MDSA	01.40	0.097	0.703	00.88	05.94	05.11
GBOB1H	03.12	03.09	02.72	02.22	05.52	05.81
GBOB1V	06.21	06.35	03.47	03.03	05.86	05.24
GBOB1A	02.32	02.19	08.1	05.77	07.72	06.66
GBOB2H	03.18	03.42	15.50	11.66	08.82	06.88
GBOB2V	06.01	05.71	05.79	03.57	07.43	06.11
GBOB2A	0.877	01.11	03.41	02.18	05.61	04.33

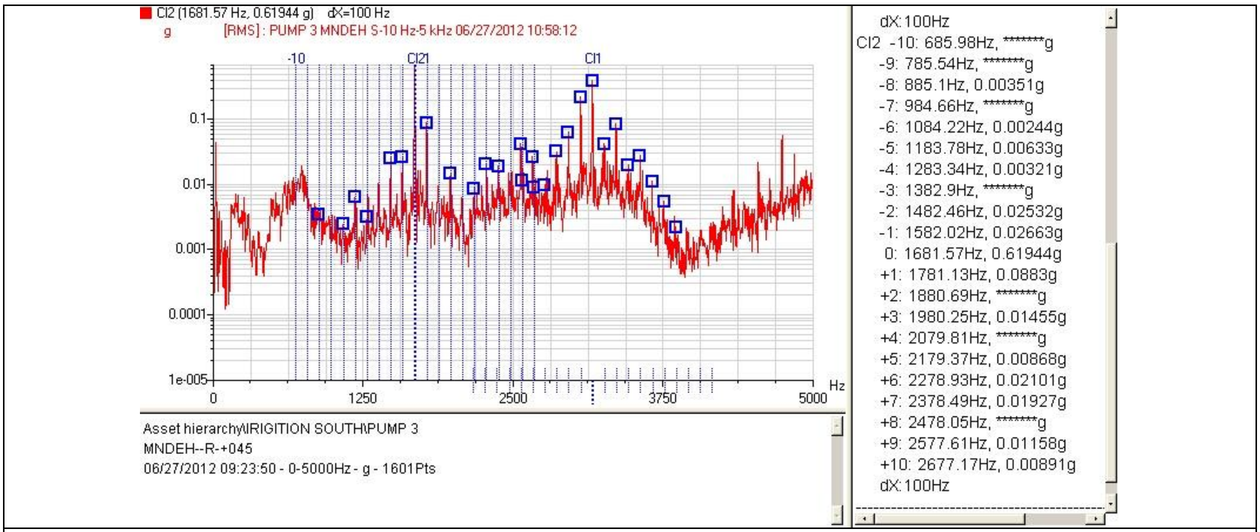
From frequency analyses, there is frequency equal frequency clutch (GUF) at rotating speed and its harmonics reached to 6.66 mm /sec as shown in **Figures (6-a, 6-b, 6-c, and 6-d).** Also, resonance problem was still found, but less than the previous, as shown in **Figure (5-a)**.

Clutch frequency values appear in the gearbox pump side in the case of full load, which indicates unbalance problem in the axial direction according to incorrect putting steel foundation under the motor over the base of concrete, as shown in **Figures (6-e** and **6-f).**

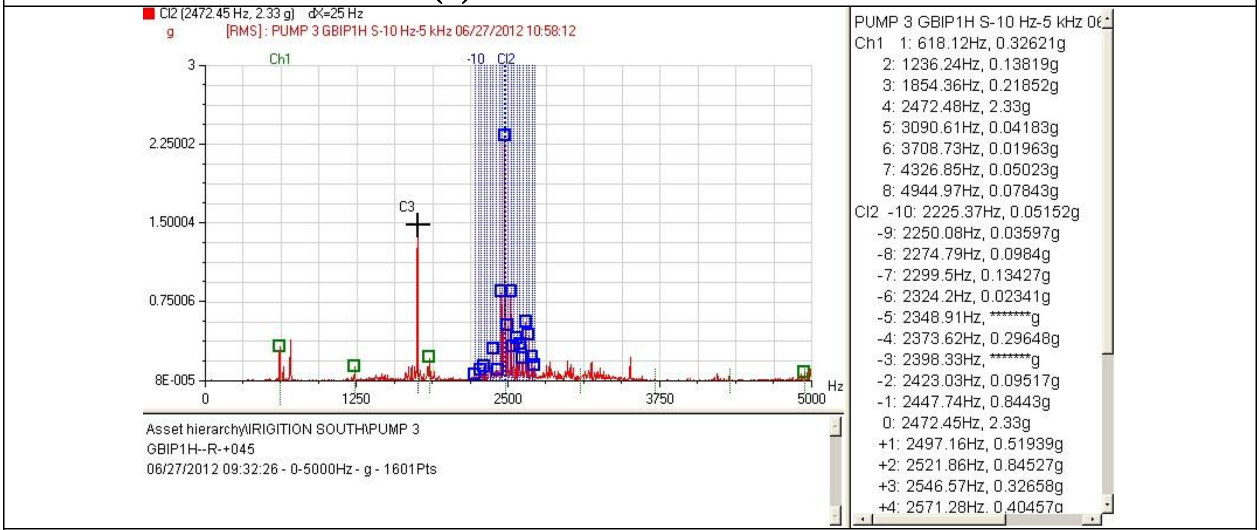


(a) motor non drive side horizontal

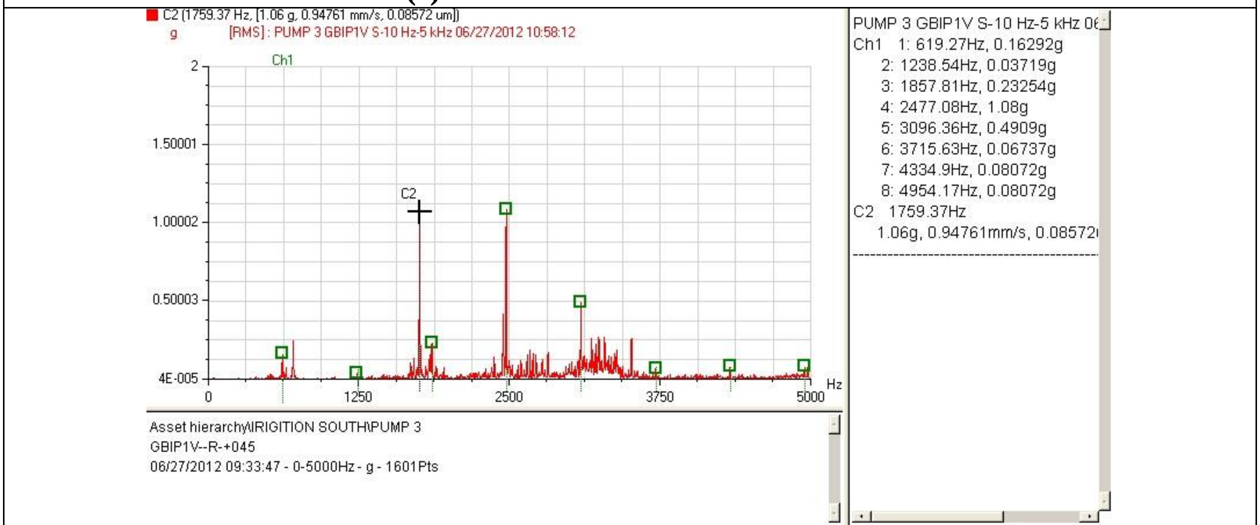
ISSN 2055-6551(Print), ISSN 2055-656X (Online)



(b) motor drive side horizontal



(c) Gear Box motor side horizontal



(d) Gear Box motor side Axial

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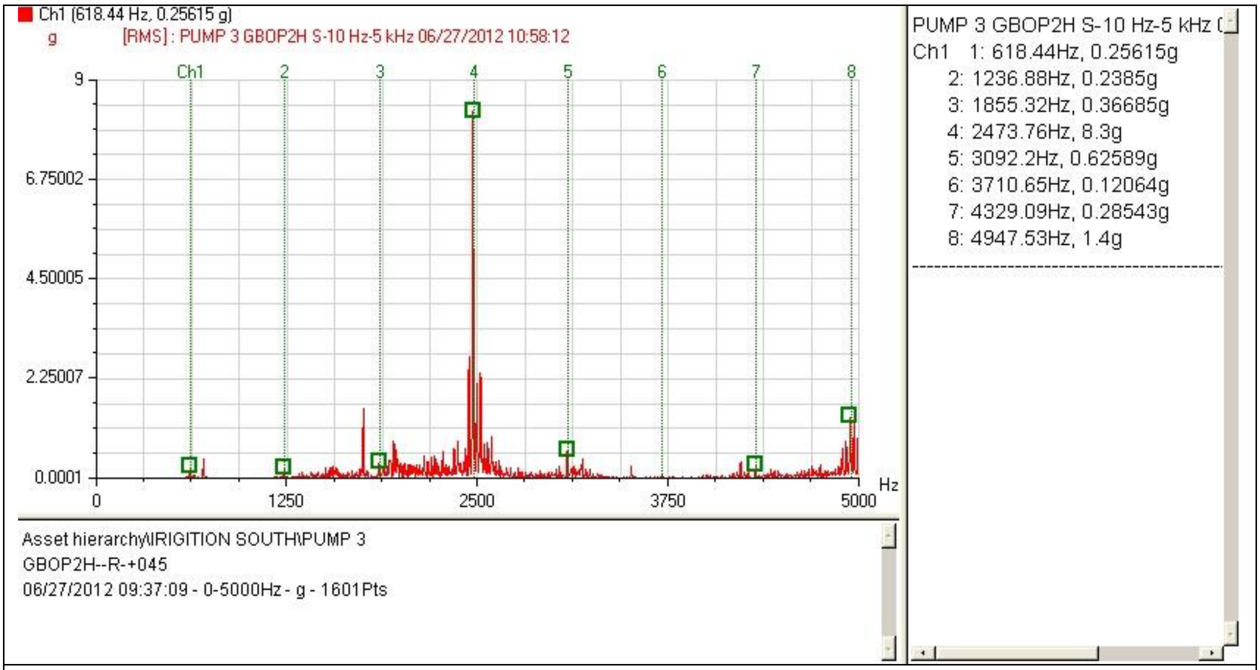
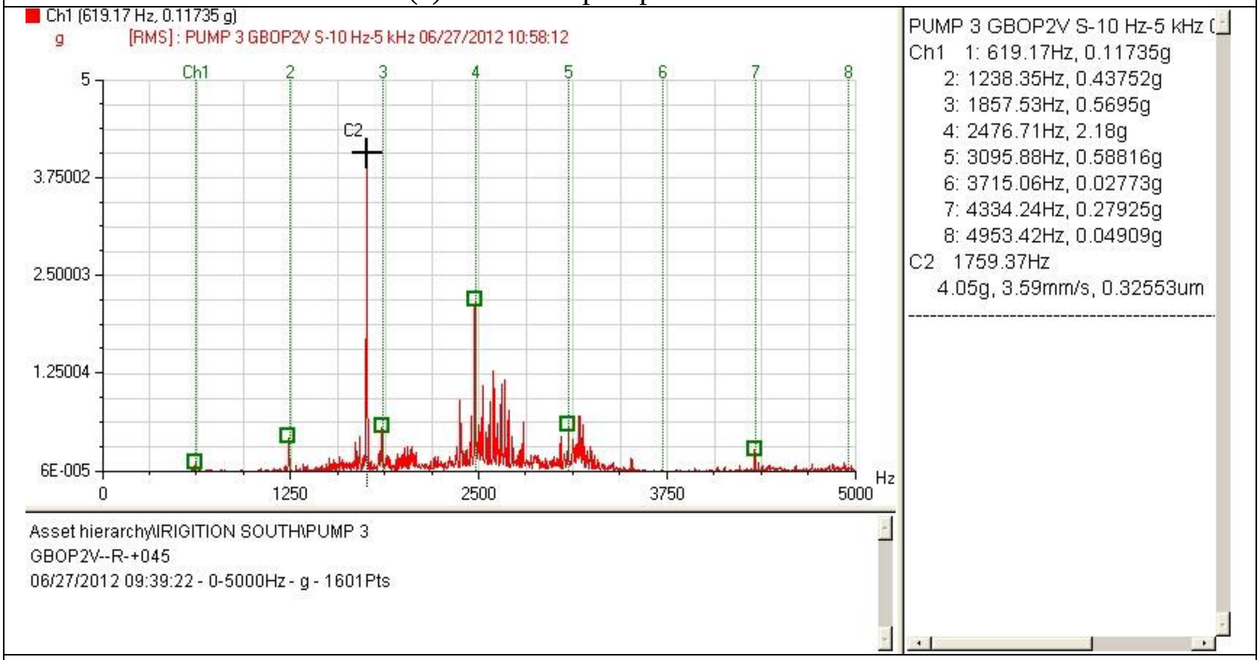


(e) Gear Box pump side horizontal



(f) Gear Box pump side vertical

Fig. (6) Frequency analyses at full load on the motor and gearbox

RESULTS & DISCUSSIONS AFTER INCREASING STEEL SUPPORTS

Measurements were repeated at full load after increasing steel supports to motor foundation are shown in **Figure (7)**. Increasing steel supports to motor foundation then, overall vibration velocity, gravity acceleration, and bearing defect factor were done with full load and with no load. Also, frequency analysis is done with full load and with no load.

ISSN 2055-6551(Print), ISSN 2055-656X (Online)

(a) Before adding steel supports	(b) After adding steel supports	(c) After increasing steel supports

Fig. (7) Photograph for Marashda (1) Pumping Station showing steel supports

Case 4: results and discussions after increasing steel supports for pump (1) at full load

Overall Vibration Velocity, acceleration, and BDF at full load were done after increasing steel supports to motor foundation. From velocity measurements and analyses it's found that improvement for all overall vibration levels, and become within the acceptable range, where the highest level is reached to 3.7 mm/sec as shown in **Table [7]**. While it's found that improvement for all gravity acceleration levels, and become within the acceptable range, where the highest level is reached to 1.47 g's as shown in **Table [7]**. Also, from measurements, analyses, and increasing steel supports to motor foundation it's found that improvement for all levels of BDF, where the highest level is reached to 4.23 as shown in **Table [7]**.

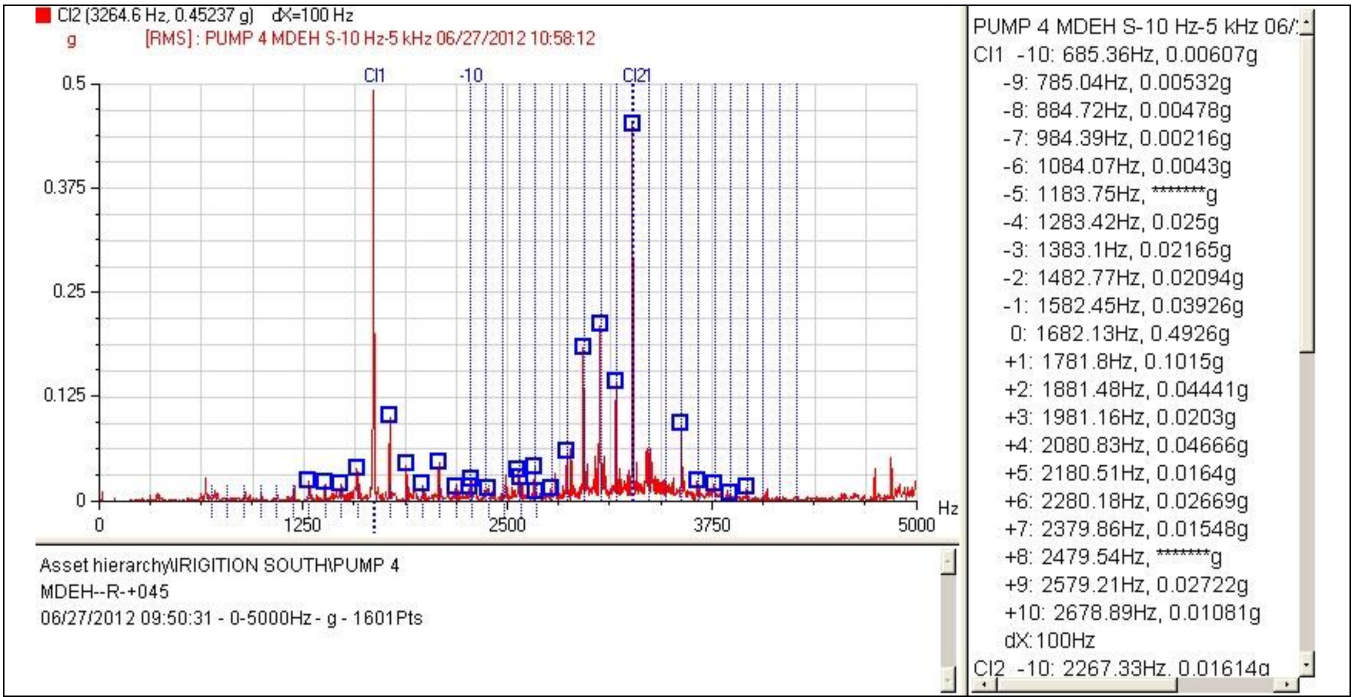
Table [7]: Overall Vibration Levels Measured after increasing supports [with full load]

Measurement Locations	Overall Velocity (mm/s)		Overall Acceleration (g's)		Bearing defect Factor (BDF)	
	Adding supports	Increasing supports	Adding supports	Increasing supports	Adding supports	Increasing supports
MNDSH	08.13	01.59	00.88	00.80	03.19	02.79
MNDSV	03.06	01.13	00.95	00.45	03.71	03.12
MNDSA	01.41	01.34	00.99	00.79	03.91	02.93
MDSH	01.09	00.75	01.19	00.92	04.58	04.23
MDSV	0.043	00.29	01.44	00.94	04.95	03.29
MDSA	0.097	00.36	00.88	00.48	05.11	03.32
GBOB1H	03.09	03.27	02.22	00.98	05.81	03.16
GBOB1V	06.35	03.70	03.03	01.03	05.24	03.28
GBOB1A	02.19	01.63	05.77	00.77	06.66	04.00
GBOB2H	03.42	03.07	11.66	01.47	06.88	03.85
GBOB2V	05.71	03.26	03.57	00.50	06.11	02.23
GBOB2A	01.11	0.781	02.18	01.03	04.33	01.15

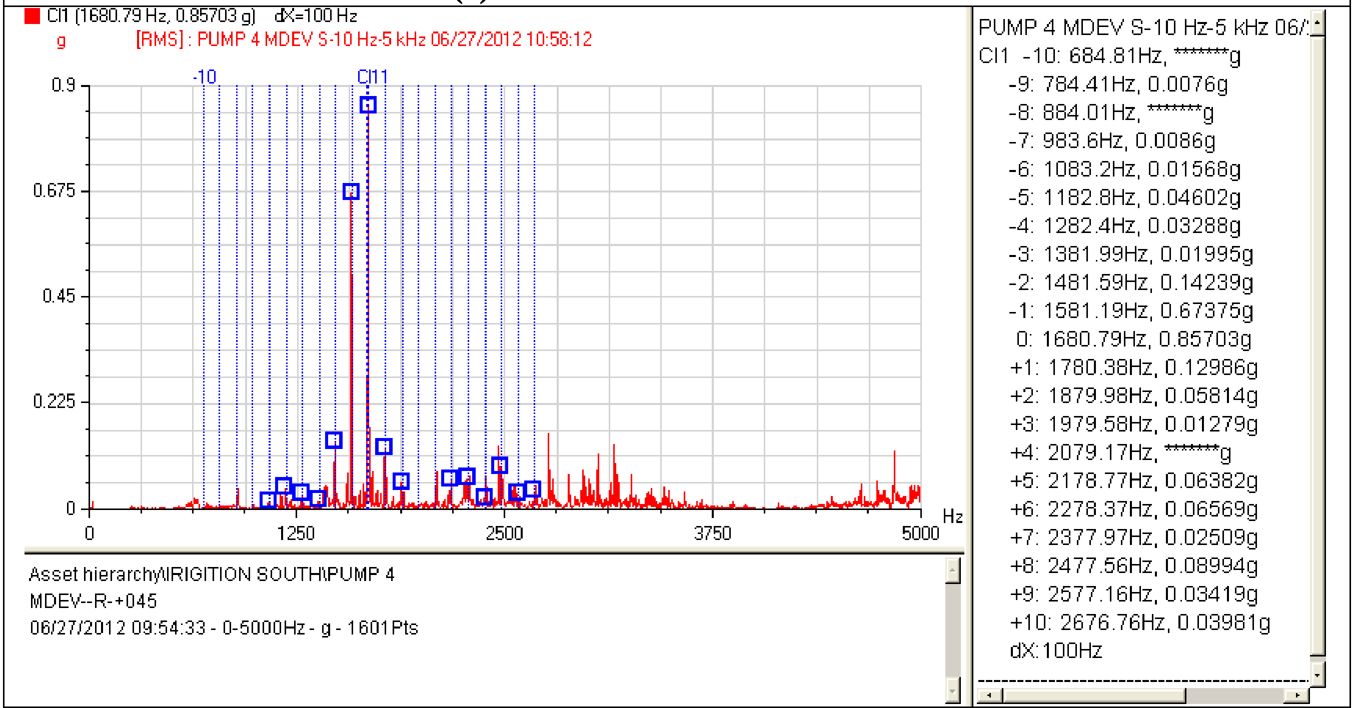
After increasing steel supports to motor foundation stronger than the previous and adding iron base under the motor foundation so, it become hardness then vibrations decreased on the motor where it reached to 1.29 mm/sec and 1.1 mm/sec respectively, as shown in

ISSN 2055-6551(Print), ISSN 2055-656X (Online)

Figures (8-a and 8-b). Also resonance problems disappeared and also frequency clutch and its harmonics were disappeared, as shown in **Figures (8-c and 8-d)**.

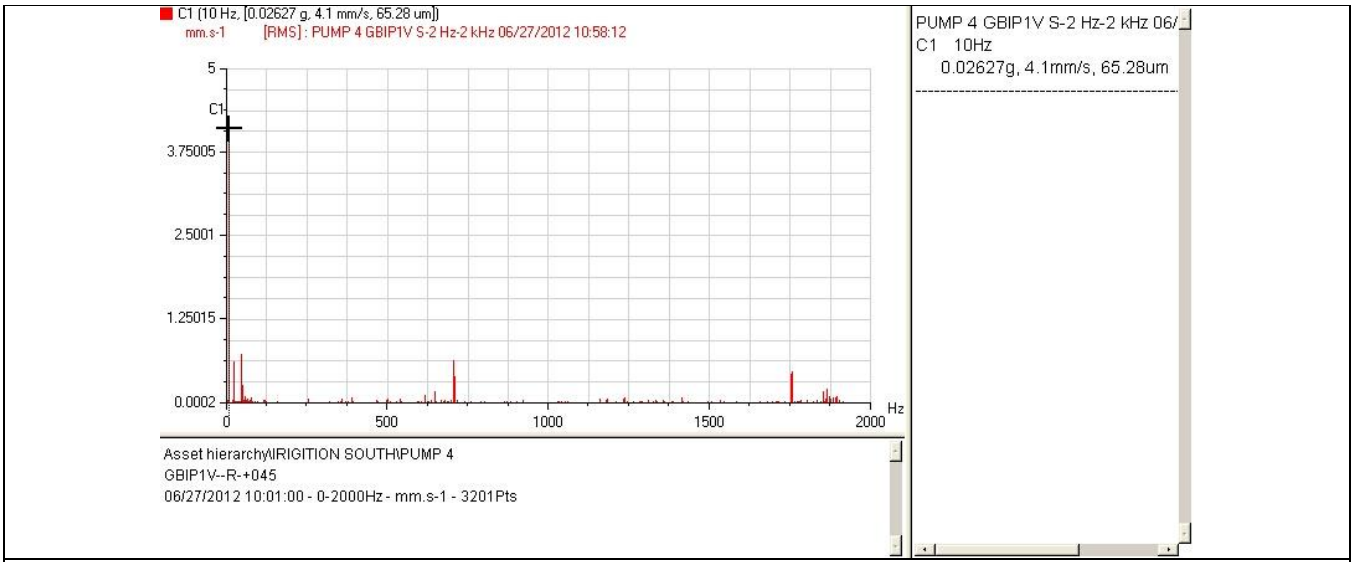


(a) motor non drive side horizontal

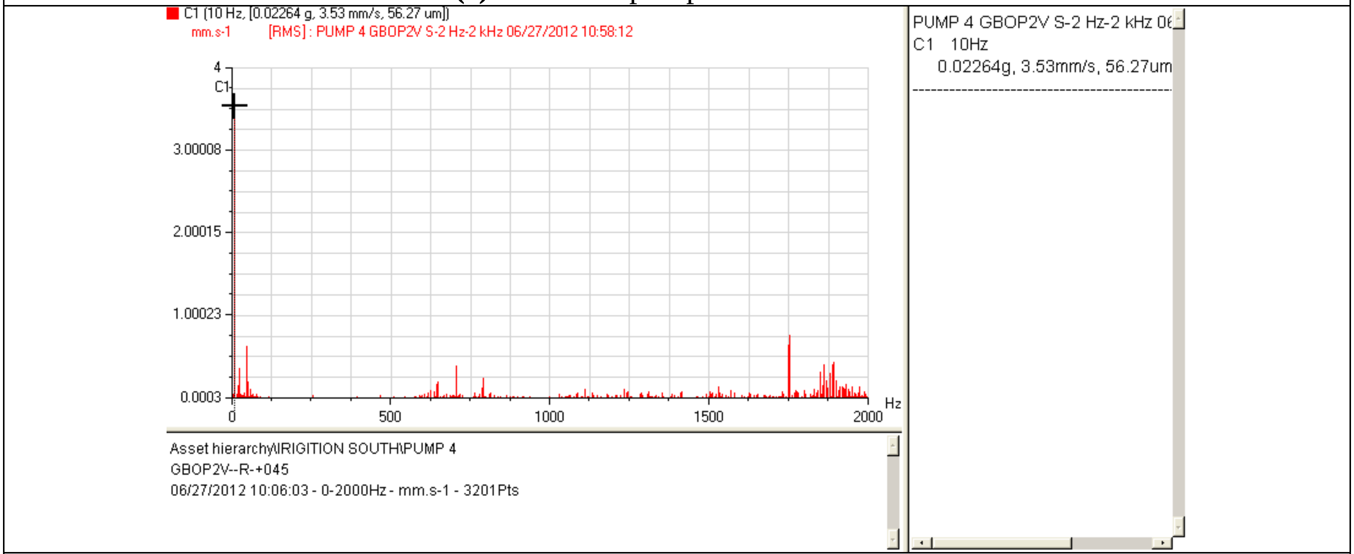


(b) motor drive side horizontal

ISSN 2055-6551(Print), ISSN 2055-656X (Online)



(c) Gear Box pump side horizontal



(d) Gear Box pump side vertical

Fig. (8) Frequency analyses at full load on the motor and gearbox after increasing supports

CONCLUSIONS & RECOMMENDATIONS

- From initial measurements, vibration levels measured on the pumps are in the danger level. .
- Frequency analysis determined the sources of vibration due to mechanical problems (motor unbalance, gear teeth, misalignment) as well as weakness of the foundation
- Different case studies are evaluated at different conditions experimentally to obtain the optimum dynamic conditions
- Adding steel supports to motor foundation gradually fixed the problem and reduced the high vibration level.

ISSN 2055-6551(Print), ISSN 2055-656X (Online)

- Adding steel supports to motor foundation reduced the velocity vibration level **53%**, reduced the acceleration vibration level **24%**, and reduced the bearing defect factor (BDF) **22%**.
- Increasing steel supports to motor foundation reduced the velocity vibration level **91%**, reduced the acceleration vibration level **91%**, and reduced the BDF **56%.**
- The dynamic characteristics of the pump structure have improved and the measured vibration level is safe.
- Vertical pump foundation should be carefully designed and strengthened to resist the dynamic loads.
- Inspection and regular maintenance is important to avoid any abnormal conditions leading to dynamic loads affecting both pump components and foundation.

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ISSN 2055-6551(Print), ISSN 2055-656X (Online)