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Early Installation Effect on the Vibration Generated by Machines

Maitham Al-Safwani

***Abstract*—**Motor vibration issues were analyzed and correlated to poor equipment installation. We had a water injection pump tested in the factory and exceeded the pump vibration limit. Once the pump was brought to the site, its half-size shim plates were replaced with full-size shims plate that drastically reduced the vibration. In this study, vibration data were recorded for several and similar motors run at the same and different speeds. The vibration values were recorded — for two and a half hours — and the vibration readings analyzed to determine when the readings become consistent. This was as well supported by recording the audio noises produced by some machines seeking a relationship between changes in machine noises and machine abnormalities, such as vibration.

***Keywords*—**Vibration, noise, shaft unbalance, shaft misalignment.

I. Introduction

THE pump is a rotating machine that is coupled to motors that rotate and vibrate. Vibration is a major issue that can cause damage to a rotary machine and to any of its parts. It results in loss of energy, increases in noise, friction and wear, and generates heat. Pump vibration could be minimized if the pump is installed correctly, its rotor is aligned and balanced, fluid flow and pressure fluctuation are controlled, and pump wear and cavitation are avoided and eliminated. There are several types of vibration monitoring instrumentation used to monitor rotating equipment vibration. This could be monitored online or off-line by measuring the equipment acceleration, velocity, or displacement. Large-sized centrifugal pumps are generally recommended to be equipped with two vibration measurement instruments per bearing, one at the x-axis and the other at the y-axis.

Per ANSI/HI 9.6.4 standard, the bearing will have 100% of its nominal life if the vibration intensity is 0.1 inches/sec, which could be reduced to 60-70% if the vibration level increases to 0.2 inches/sec [1]. The pump vibration limit is set by several standards, including: the American Petroleum Institute (API), standard 610, International Standards Organization (ISO) standard 10816, Hydraulic Institute (HI), and ANSI/HI standard 9.6.4. Saudi Aramco standards comply with PMI 610 and ISO 13709 for Centrifugal pumps.

II. Vibrations Presentation in Time Wave Front and Fast Fourier Transform

A waveform is time domain data that present the amplitude of different types of signals, such as the vibration amplitude with respect to time. The wave front resolution, Fig. 1, should be clear enough to be useful to obtain important graph data such as amplitude, period, distortion, frequencies of different signals and spikes. Using a Fast Fourier Transform, Fig. 2, the time wave front can be represented mathematically as a series of sines and cosines and can be easily analyzed and understood.

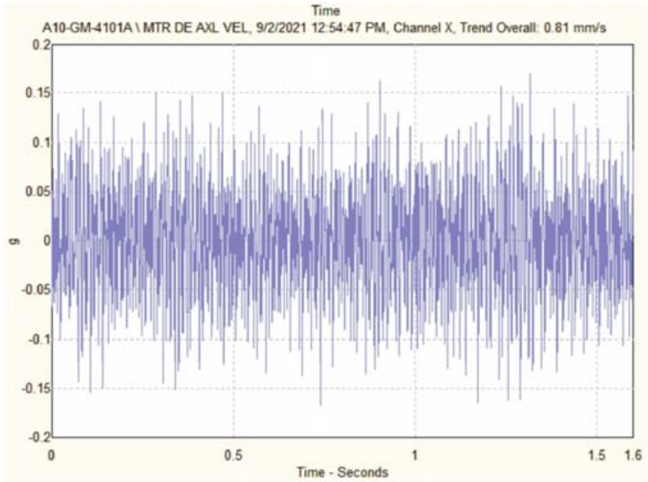

Fig. 1 Time Wave Front Representation

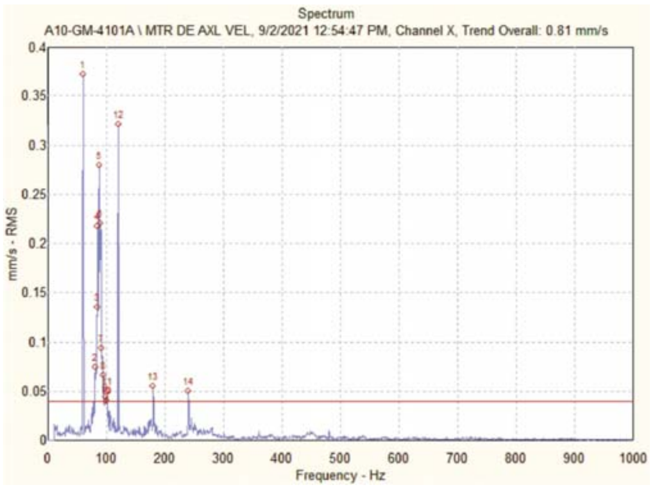

Fig. 2 Fast Fourier Transform Representation

III. Causes of Vibration

There are several causes of vibration in rotating machines such as looseness of the machine parts, bearing faults, defective gears or belts, and electrical issues. The rotating machine

Maitham Al-Safwani is with Saudi Arabian Oil Company (Saudi Aramco), Dhahran, Saudi Arabia (e-mail: Maitham.Safwani@aramco.com).

consists of structural and rotating parts. Structural parts include machine base mounts, split casings, and the bearing caps housing; while rotating parts consist of fans, bearings, impellers and couplings. Casting defects can cause vibration as well, such as casing with blow holes from trapped air, gases and vapor. Bearing faults occur if the wrong lubrication is used, or if bearings are mounted incorrectly or deployed for the wrong application. Electrical faults can be due to shorted windings and breakdown of insulation. Defective gears or belts occur due to misalignment, excessive load, gear tooth wear or broken teeth.

IV. Diagnosis of Machine Problems

Vibration is a very important parameter to measure for troubleshooting and diagnosing problems with rotating equipment. Vibration amplitude expresses the movement of a vibrating object in terms of displacement, velocity and acceleration. Displacement measures the distance a machine shaft moves in relation to a reference point. It is measured on mil, one mil = 0.001 inch. Velocity measures displacement with respect to time in in/sec. Acceleration measures changes of velocity relative to time and is measured in in/sec^2.

If a machine operates at a certain rpm. Then vibration will be diagnosed based on the orders of operating speed. For example, if a machine operates on 500 rpm, then its first order is 500 rpm and second order is 1000 rpm, and so on.

Shaft Unbalance

Machine balance is achieved by equal spacing and distribution of the weights of the rotating parts around the centerline. The ISO defines unbalance as the condition which exists in a rotor when vibratory force or motion is imparted to its bearings as a result of centrifugal forces [2]. In another definition, unbalance is the uneven distribution of mass around a rotor's rotating centerline, which means if the weights of the rotating parts are not spaced equally around the centerline of the shaft, it results in unbalance. Shaft unbalance can be caused by deposit build up, corrosion or wear, broken parts and pump' assembly error.

Machine unbalance in Fig. 3 is deduced by measuring the radial (perpendicular) vibration based on the amplitude of the first order of the machine speed. Spectrum interpretation of the measured vibration indicates the main cause of vibration [3].

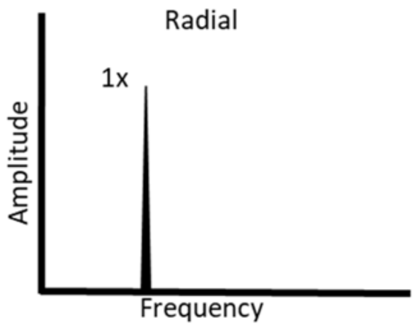

Fig. 3 Vibration due to Unbalance

Misalignment

There are two types of the misalignments: angular misalignment, where two shaft centerlines meet at an angle to each other, and parallel misalignment, where two shaft centerlines are parallel to each other but not in-line and have an offset; or a combination of both.

Angular misalignment results on machines pulling and pushing each other, which generates an axial vibration at the first order, while parallel misalignment results in one machine pulling the other for half of each cycle and pushing it for the other half. This results in radial vibration at the second order. If the machine has angular and parallel misalignment, then axial vibration and radial vibration of both first and second orders will appear; and of the third order as well, as in Fig. 4.

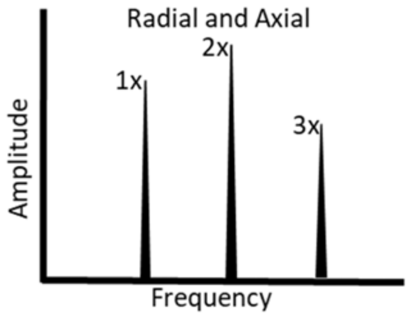

Fig. 4 Vibration due to Misalignment

Mechanical Parts' Looseness

Mechanical parts looseness relates to structure and internal rotating parts looseness. Structure or internal parts looseness produces radial vibration at different orders and sub-order of the speed, as shown in Fig. 5.

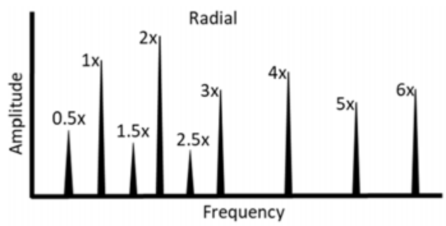

Fig. 5 Vibration due to Parts' Looseness

Vibration Severity

TABLE I
VIBRATION SEVERITY

Vibration Severity		Velocity in/sec	Velocity mm/s	Acceleration G	Action
Ultra levels	Less than	0.05	1.3		No action is required
Excellent levels		0.1	2.5	0.1	
Good levels		0.2	5	0.35	
Fair levels		0.3	7.5	0.5	
Rough levels	Higher than	0.4	10	0.75	Immediate action needs to be taken
Very rough levels		0.6	15	1	
Danger levels		0.8	20	1.5	
Breakdown levels	Equal or higher than			2.5	

For displacement, it depends on the RPM, for example, 1 mil at 1500 rpm is excellent, while 1 mil at 35,000 rpm is dangerous and not accepted.

Table I was developed based on one of the internet resources, it is applicable to all machines except diesel engines and rock crushers [4]. For diesel engines and rock crushers, the vibration should not exceed 0.2 in/sec (2.5 mm/s) which equals to 0.35 G (G = 33.2ft/sec^2 or 9.8 m/s^2). G is the force of gravity.

V. Monitoring Machines by Measuring the Vibration

Monitoring of vibration allows detection and avoidance of machine failure. Vibration is expected to last for three to four months before the machine starts to generate high noise, heat and breaks down as shown in Fig. 6 [5].

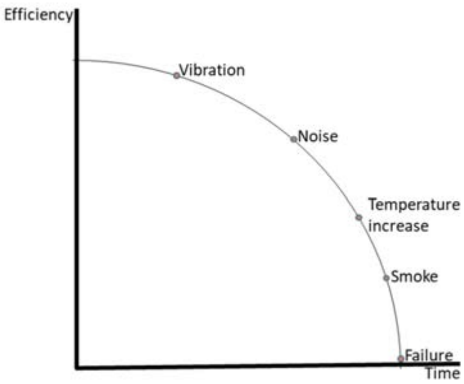

Fig. 6 Machine from Vibration to Failure

Bearing Defect Frequencies

There are four frequencies identified as bearing defect frequencies. These frequencies are BPFO (Ball Pass Frequency Outer) which is outer race failing frequency; BPFI (Ball Pass Frequency Inner) which is inner race failing frequency; BSF (Ball Spin Frequency), which is rolling element failing frequency, and FTF (Fundamental Train Frequency), which is cage failing frequency. These failing frequencies could be calculated using the formulas in Fig. 7 [6].

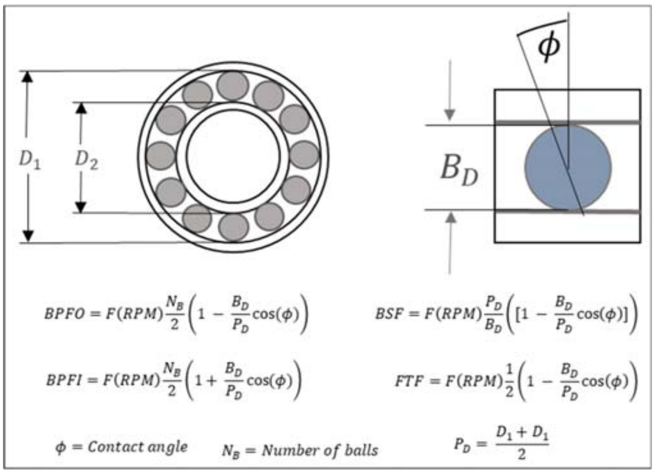

Fig. 7 Bearing defect frequencies

The contact angle is the angle between a line connecting the two contact points between the ball and inner and outer raceways.

Vibration formulas: Vibration is measured based on displacement, velocity or acceleration. These parameters are related to each other as shown below:

Velocity could be obtained based on the displacement and RPM using the equation:

$$\text{Velocity (in/sec)} = \frac{\text{D(mils)xF(RPM)}}{19{,}100}$$

RPM stands for revolution per minute.

Acceleration could be calculated from velocity and RPM using the equation:

$$\text{Acceleration (G)} = \frac{\text{V(in/sec)xF(RPM)}}{3{,}690}$$

Recommended frequency ranges for different amplitude units [3]:

- Displacement Units: < 600 cpm (< 10 Hz)
- Velocity Units: 300 - 120,000 cpm (5 - 2,000 Hz)
- Acceleration Units: > 60,000 cpm (> 1,000 Hz)

Noise Level Analysis

Measuring the noise level around an operating machine could provide an early sign of an abnormal condition. Several machines were checked for noise level and it was found that some of the machines had higher noise levels than other similar machines. Having vibration records should be annexed with the measured noise level of the machines; at different sides of the machine to provide a better outcome from the machine condition analysis. This will complement the weakness of the vibration sensors and method designed to measure a specific range of harmonics. Below is an example of the audio noise level, while no impact was noticed on the measured audio (noise) level below 2 kHz, while the audio (noise) level increases 15 dB between 3 kHz and 10 kHz after turning on the tested motor as shown in Fig. 8. From this result, it could be concluded that the noise level could be used to detect equipment malfunction and could be used to support the vibration measurements, and may replace it in the future.

A small trial was done to observe the characteristics of the audio noise around one of the rotating machines, an electrical generator. Some changes in the signal amplitude were found to be spiking up and down. The vibration was measured on the machine casing, and the machine had a high vibration of 6.7 mm/s on one side, and the vibration increased to 14.4 mm/s at the back side of the generator. The increases were most likely due to part looseness. The main benefit of this trial is to prove that the noise reading is important to record, as it will provide hints about machine conditions. The audio noise application is available in smart phones and could detect the spikes generated by the machine, as shown in Fig. 9.

Installation Impact on Vibration

The vibrations — in two fuel oil pump motors — were recorded for two and a half hours. It was noticed that one motor had higher vibration levels. These two motors were running at the same speed and used for a similar application, and both operated at 4.16 kV. Although the vibration of the two motors was within the accepted limit, as shown in Fig. 10; however, it is easy to tell that the live span for the motor of higher vibration will be shorter than that motor of the lower vibration. The vibration starts at the installation stage and the vibration level increases during the equipment operation. Motor which has more vibration after installation is expected to fail faster — whether the motor meets the vibration limit or not. Machine health is mainly related to the initial installation of these motors.

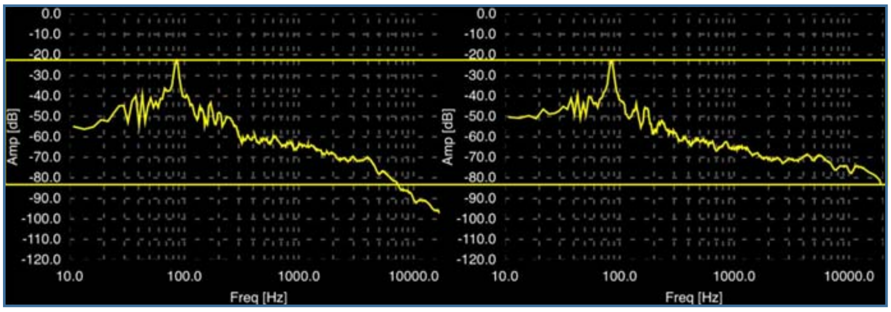

Fig. 8 Audio and Noise Analysis of a Rotating Machine

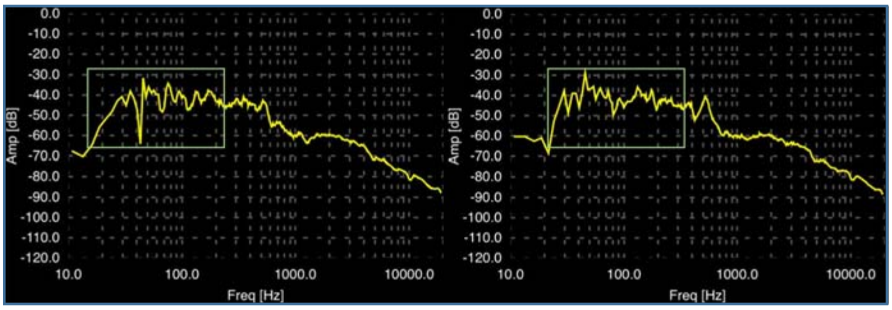

Fig. 9 Spike on Audio Signal

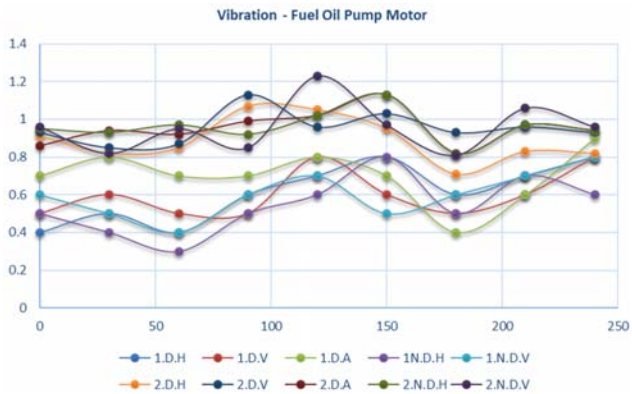

Fig. 10 Measured Vibrations of Two Identical Motors

Another example was taken for four similar motors used for boiler feed water pumps and shown in Fig. 11. The measured vibration of motor in the driven side of the motor become stable with time, while for the non-driven side, radial vibration fluctuated in both the horizontal and vertical planes, which could be considered as an indication of a slight looseness issue. The vibration of motor 2 becomes more stable with time. All of its measured vibrations are below 0.9 mm/s, and among all other motors, it looks like that this motor is the most appropriately installed one. For motor 3, the vibration tends to increase with time, while for motor 4, the vibration reading is unstable at the motor end in the radial vertical plane and axial plane, which is a sign of slight looseness which could increase in future.

VI. Example of Vibration Measurement

Vibration measurements were done for several rotating equipment items. Fig. 12 illustrates one example of the vibration recorded for a Boiler Feed Water Pump motor that exceeded the accepted vibration limit of 2.5 mm/s. Fig. 12 shows a high vibration at the first order at the Axil plane, which is related to the unbalance issue. It was found that the unbalance issue was caused by a shaft's lose fan. After the fan was fixed, the vibration level was reduced to an acceptable level.

VII. Conclusion

Poor installation of rotating equipment results in vibration issues that become aggravated with time. Following standard vibration values will help protect the bearing life span. This could be improved if the vibration limit was minimized during the installation. The vibration values were recorded to compare between the new equipment used for the same application and it was noticed differences in vibration values because of some issues with the initial installation. The produced noise was recorded for some machines. The spiked changes on machine noises lead to discovering machine abnormalities due to high vibration.

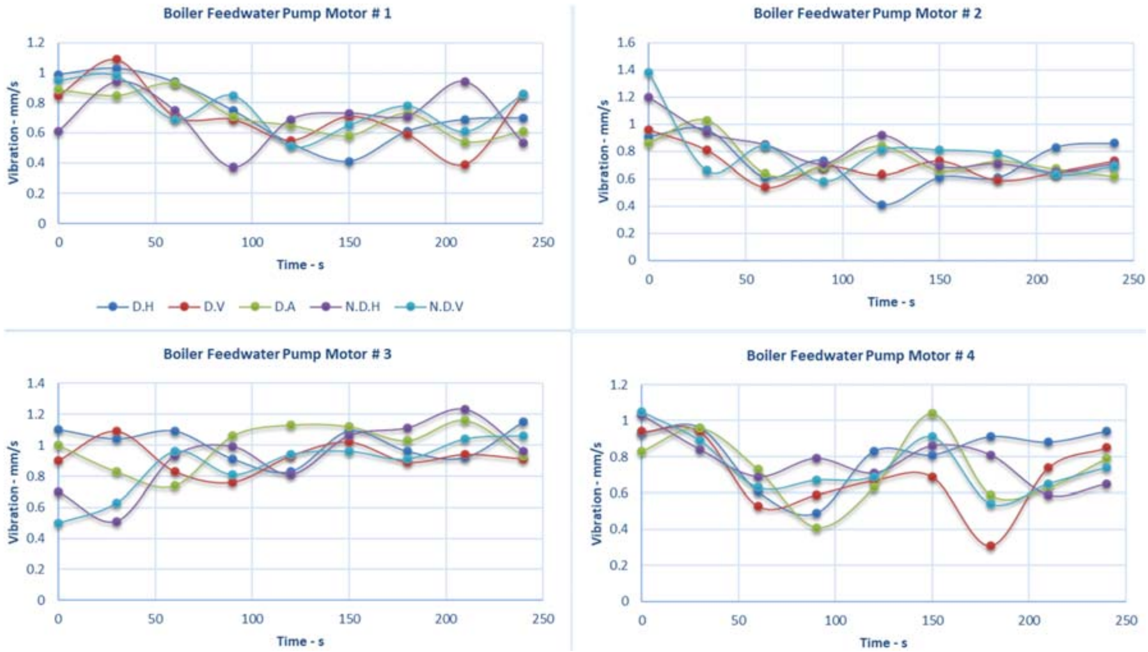

Fig. 11 Measured Vibrations of Four Identical Motors

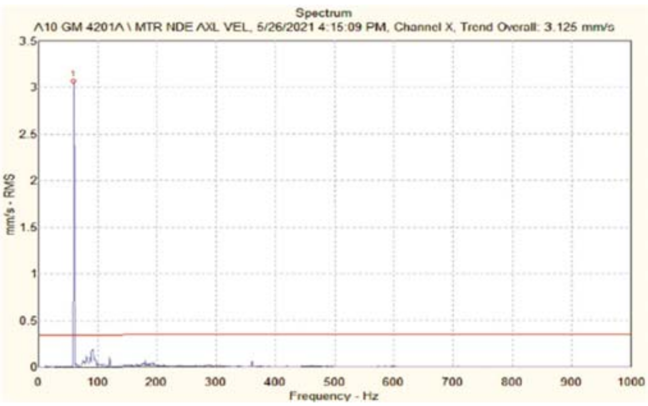

Fig. 12 Vibration due to Shaft Unbalance Caused by Fan Looseness

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