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Vibration analysis of centrifugal pumps

Introduction

It was mentioned previously that there are literally hundreds of specific mechanical and operational problems that can result in excessive machinery vibrations. However, since each type of problem generates vibration in a unique way, a thorough study of the resultant vibration characteristics can go a long way in reducing the number of possibilities -- hopefully to a single cause.

There are many ways that a pump's vibration can be studied and analyzed. It is beyond the scope of this article to cover all analysis techniques. Here is introduced the fundamentals of vibration analysis and the outline of a simple, logical and systematic approach that has been proven successful in pinpointing the vast majority of common day-to-day machinery problems.

Characteristics needed to define vibration include:

- Frequency
- Displacement
- Velocity
- Acceleration

Instruments for measuring and analyzing machinery vibration are available in a wide array of features and capabilities but are generally categorized as:

1. Vibration meters (hand held type – portable)
2. Vibration Frequency analyzers (FFT analyzers)

Defining FFT Spectral parameters

FFT can be taken any time, whether for a detailed analysis or for routine predictive maintenance checks. It is necessary to define or specify the FFT spectral parameters. These parameters include:

1) Amplitude units: Displacement, Velocity or Acceleration
2) F_{max}: The range of vibration frequencies to be analyzed
3) Frequency units: CPM or Hz
4) Number of lines of resolution: The accuracy of displayed vibration frequencies
5) Number of spectral averages: How many FFT's are taken and amplitude averaged to minimize random and transient events

Selecting F_{max}

The first and perhaps most important decision that must be made in obtaining an FFT is the F_{max} or maximum range of frequencies that will be analyzed and displayed. Of course, the selected F_{max} must be high enough to include all significant, problem-related frequencies. However, the higher the F_{max}, the lower the accuracy of measured frequencies. Therefore, the F_{max} selected should be no higher than needed to detect problem-related vibration frequencies.

Following are the steps discussed in detail to identify the vibration problems.

1) Define the problem:

The first step in solving a vibration problem or any problem for that matter is to define the problem. In other words, "why is a vibration analysis needed? It is difficult to solve the problem when one doesn't even know the problem is or what the desired outcome should be.

Following is a list of reasons for performing vibration analysis.

a) Establish baseline data for future analysis needs.
b) Identify the cause of excessive vibration.
c) Identify the cause of significant vibration increase.
d) Identify the cause of frequent component failures.
e) Identify the cause of structural failures, viz., structure, foundation or piping, etc.
f) Identify the source of the noise problem.
g) Identify a reason for not achieving the desired quality/life of parts. For example, surface finish/tolerances of parts in case of machine tools, desired life of components like bearing, shafts etc.
h) Identify why a machine fails to meet an established performance standard.

2) Determine the machine/pump history:

Whenever a machine/pump has excessive vibration and a history of premature failures, the obvious questions that need to be answered are:

a) When did the problem start? And
b) Were any changes made to the machine/pump before the problem occurred?

In many cases, the answers to these questions can provide valuable insights into the possible cause of the problem. In fact, in some cases, the answers to these questions may identify a cause that is so obvious that a detailed vibration analysis is totally unnecessary.

2.1 When did the problem start?

There are basically three possible answers to this question:

a) The vibration increased gradually over a period of time.

This trend of increasing vibration may have been detected by routine periodic checks taken as a part of a predictive maintenance programme. Of course, no machine or machine component will last forever. Eventually things do wear out. The obvious things to check would include:

- Bearing wear or deterioration.
- Deterioration of base, foundation, grouting, etc.
- Wear, corrosion or build-up of deposits on rotating components that may have affected the balance.
- Settling of base or foundation that may have affected the alignment or piping strains.
- Blockage of filters on fans or strainers on pumps that may affect the flow characteristics.
- Breakdown in lubrication needs such as gear couplings that will affect their ability to compensate for misalignment.

b) The machine has always run rough, even when it was new.

Just because a machine is new doesn't necessarily mean that it is free from problems. If a machine has never performed smoothly, some possible reasons may include:

- The machine is mounted on a weak or resonating base or foundation.
- Some element of the system, such as associated piping, may be in resonance.
- Rotating components are not balanced to proper specifications.
- The machine was not aligned properly, perhaps for thermal growth.
- Piping was not aligned properly, resulting in piping strain.
- Pump performance characteristics do not meet performance needs.
- Pump was manufactured incorrectly in terms of dimensional tolerances including component fits, eccentricity, etc.

c) The vibration increased abruptly.

Some of the more common causes of immediate or abrupt changes in pump vibration include:

- Changes in pump speed.
- Modification to the pump or related component.
- Modifying the pump's base, foundation, piping, etc. may result in resonance, distortion or changes in alignment, flow conditions or other problems that can

result in an increase in vibration.

- Replacement of parts. Simply replacing a coupling, pulley or other rotating element can result in vibration increase if the part has not been properly balanced or manufactured to certain quality control standards.

3) Determine machine/pump details:

Some of the important detailed features of the machine that need to be known for accurate analysis include:

1. The rotating speed (rpm) of each machine component.
2. Type of bearings.
3. Number of fan blades
4. Number of impeller vanes.
5. Number of gear teeth.
6. Type of coupling.
7. Pump critical speeds.
8. Background vibration sources.

4) Obtain Horizontal, Vertical and Axial spectrums (FFTs) at each bearing of the machine/pump set train.

In many cases, the analysis steps carried out above may be sufficient to pinpoint the specific problem causing excessive vibration. If not, the next step is to obtain a complete set of amplitude versus frequency spectrums or FFTs at each bearing of the pumpset train. For a proper analysis, the pump should be operating under normal conditions of load, speed, temperature, etc.

In order to ensure that the analysis data taken includes all the problem -related vibration characteristics. It is easy to evaluate and interpret if the following recommendations are referred.

- Use the same amplitude range (scale) for all FFTs, since the pump vibration amplitude versus frequency characteristics will be presented in the form of graphic plots or FFTs. It is important to use the same amplitude range for each FFT to simplify the comparison of the data obtained at each bearing and measurement direction. If the data is presented with different amplitude scales, the interpretation and evaluation of the data becomes extremely tedious, time-consuming and confusing.
- Define spectral parameters that will cover all important vibration frequencies: great care should be taken in choosing Fmax and lines of resolution so that it ensures that all important vibration frequencies are detected.

5) Interpreting the data

Once horizontal, vertical and axial FFTs have been obtained for each bearing of the pumpset train, the obvious next question is: "What is the data telling me?" Essentially, amplitude versus frequency spectrums or FFTs serve two very important purposes in vibration analysis:

- Identify the machine component (motor, pump, gear box, etc.) of the machine train that has the problem.
- Reduce the number of possible problems from several hundred to only a limited few.

5.1 Identifying the problem component based on frequency

5.2 Identifying the problem component based on amplitude

5.3 Reducing the list of possible problems based on frequency

In addition to identifying the problem, the pump component based on the frequency and/or amplitude characteristics, the second purpose of FFT analysis data is to limit or reduce the list of possible problems based on measured vibration frequencies.

As stated earlier, each mechanical and operational problem generates its own unique vibration frequency characteristics. Therefore, by knowing the vibration frequency, list out the problems that cause or generate a particular frequency. This greatly reduces the long list of possibilities.

The following chart lists the most common vibration frequencies as they relate to pump rotating speed (rpm), along with the common causes for each frequency.

5.5 Comparing tri-axial (horizontal, vertical and axial) data

Once the list of possible problems has been narrowed down to a limited few, the remaining list can usually be reduced even further by comparing the vibration characteristics measured in horizontal, vertical and axial directions.

There are basically two comparisons that need to be made from the data in the figure. First, how do the horizontal and vertical readings compare; and secondly, how do the radial readings (horizontal and vertical) compare to the axial readings.

5.6 Comparing Horizontal and Vertical Readings

When comparing the horizontal and vertical data, it is important to take note of how and where the pump is mounted and also how the bearings are mounted to the pump. Basically, vibration analysis needs to develop a feel for the relative stiffness between horizontal and vertical directions in order to see whether the comparative horizontal and vertical readings indicate a normal or abnormal situation. Pumps mounted on a solid or rigid base may be evaluated differently than pumps mounted on elevated structures or resilient vibration isolators such as rubber pads and springs.

To explain the significance of machine stiffness, if a rigidly mounted machine has higher vibration in a vertical direction than the horizontal direction, this would be generally considered as "abnormal" and may indicate looseness or weakness. On the other hand, if the machine is mounted on springs or rubber pads, a higher amplitude in the vertical direction may not be considered unusual or an indication of structural problems.

Another factor that needs to be considered is the "ratio" between horizontal and vertical amplitudes. As explained, it is not unusual for rigidly mounted machines to have a higher amplitude of vibration in the horizontal direction, compared to the vertical direction. However, the ratio between horizontal and vertical amplitudes should be checked to see if it is normal or indicative of some unusual problem. As a normal unbalance response, it is not unusual for machines to exhibit the ratios between the horizontal and vertical amplitudes of 1:1,2:1,3:1 or 4:1, depending upon a particular installation.

VIBRATION FREQUENCIES AND THE LIKELY CAUSES

Frequency in terms of rpm	Most likely causes	Other likely causes and remarks
1 X RPM	Unbalance	1. Eccentric journals, gears or pulleys. 2. Misalignment or bent shaft—if high axial vibration 3. Bad belts 4. Resonance 5. Reciprocating forces 6. Electrical problems
2 X RPM	Mechanical looseness	1. Misalignment —if high axial vibration 2. Reciprocating forces 3. Resonance 4. Bad belts
3XRPM	Misalignment	Usually a combination of misalignment and excessive axial clearances (looseness)
Less than 1 X RPM	Oil whirl (less than ½ RPM)	1. Bad drive belts 2. Background vibration 3. Sub-harmonic resonance 4. "Beat" vibration
Synchronous (AC line frequency)	Electrical problems	Common Electrical problems include broken rotor bars, eccentric rotor, unbalanced phases in poly-phase systems, unequal air gap.
2 X synch Frequency	Torque pulses	Rare as a problem unless resonance is excited
Many times RPM (Harmonically related freq.)	Bad gears Aerodynamic forces Hydraulic forces Mechanical looseness Reciprocating forces	Gear teeth times RPM of bad gear Number of fan blades times RPM Number of impeller vane times RPM May occur at 2,3,4 and some times higher harmonics if severe looseness
High freq. (not harmonically related)	Bad anti friction bearings	1. bearing vibration may be unsteady-amplitude and frequency 2. Cavitation, recirculation and flow turbulence cause random, high frequency vibration. 3. Improper lubrication of journal bearings (friction excited vibration) 4. Rubbing

Location	Velocity rms. (mm/sec)			Displacement (peak to peak) micron		
	Hor.	Vertical	Axial	Hor.	Vertical	Axial
Pump DE bearing	13.4	20	12	127	136	155
Pump NDE bearing	3.17	2.6	3.1	21.6	24.6	30

Location	Velocity rms. (mm/sec)			Displacement (peak to peak) micron		
	Hor.	Vertical	Axial	Hor.	Vertical	Axial
Pump DE bearing	0.6	0.68	1.3	3.6	11	5
Pump NDE bearing	0.83	1.41	3.0	5	9	9

In other words, it is not unusual for a rigidly mounted fan, motor or pump to have a vibration amplitude at 1XRPM as much as four times higher in the horizontal direction than the vertical direction due to unbalance. Ratios beyond 4:1 are somewhat unusual and typically indicate an abnormal condition such as looseness or resonance.

5.7 Comparing Radial (Horizontal and Vertical) Data To Axial Data

The second important comparison that needs to be made to tri-axial analysis data is how the radial (horizontal and vertical) readings compare to axial readings. A relatively high amplitude of axial vibrations is normally the result of:

- Misalignment of couplings
- Misalignment of bearings
- Misalignment of pulleys or sheaves on belt drives.
- Bent shafts
- Unbalance of "overhung" rotors

As a general rule, any time the amplitude of axial vibration exceeds 50% of the highest radial (Horizontal and Vertical) amplitude, the possibility of a misalignment or bent shaft condition should be considered. Of course, extremely high amplitudes of vibration may also be due to resonance or unbalance of an overhung rotor.

Most common machinery problems are as given below.

1) Unbalance
2) Bent shaft
3) Misalignment
4) Looseness of rotor system
5) Eccentricity problems
6) Resonance
7) Defective rolling element bearing
8) Journal bearing problems
9) Aerodynamic/hydraulic problems
10) Electric (Induction) motor problems
11) Gear problems
12) Belt drive problems

Case study of centrifugal pump

In one of the horizontal split case pump vibration analysis carried out.

The pump initially exhibited the following vibrations at operating frequency, when coupled to an electric motor of 380 kW, 4 pole.

From the above values and spectrum analysis reports, it indicates that vibrations are not in the good zone or within acceptable limits as per the governing standards of the Hydraulic Institute for centrifugal pump and ISO 10816-1. The standard gives the machinery classification, relationship between acceleration, velocity and displacement, evaluation zones and vibration severity range, etc. It is not included in this report due to space constraints.

The vibrations are peak at 1 X RPM, which indicates the misalignment or unbalance condition along with bearing fitment problem.

To reduce the vibrations, the pump was dis-assembled and inspected for the following.

1) Pump and motor half coupling bore dimensions along with key width. It was observed that the key width was more by 2 mm. Also the weight of coupling bush and pins were taken and variations found.

2) Concentricity of coupling with respect to PCD of coupling bush. It was out of tolerance.

3) Dynamic balancing of rotating unit with coupling and bearings. Prior to the initial test, only the impeller was dynamically balanced. After the initial test, the rotating unit balanced along with pump half-coupling, bearings, shaft sleeve, etc.

4) Concentricity of other parts such as bearing housing, casings inspected and it was observed that they are out of specification.

5) Shaft run out.

6) Hydraulic dimensions for uniform velocity at outlet.

7) Coupling alignment after re-assembly.

After rectifying with respect to the above parameters and with strengthened foundations, the pump was put again for testing. It exhibited the following vibrations. Spectrum analysis was also taken.

These vibrations are within the good zone and are acceptable.

Summary and Conclusion:

A spectrum analysis has been developed to detect the vibrations for proper analysis. It can be seen that if proper analysis is carried out, vibrations can be reduced considerably.

Vibration analysis can be used to detect and identify the cause of vibrations by knowing the frequency of vibration and its amplitude. Also, vibration can be compared in various directions for analysis. However, this demands an FFT analyzer instrument and a knowledge of it.

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