Experiment (7)
Shaft Balancing and Bearing Faults

Introduction

In the last experiment, fundamentals of signals waveforms and DAC systems were introduced. Also, an accelerometer was used to measure the vibration signal of a beam. All rotating machinery vibrates while in operation and any abnormality in these vibrations is a common indication of impending failure. This indication makes signature analysis a common tool in predictive maintenance. One good way to do this analysis is to transform the machine's total vibration wave form to the frequency domain. In this experiment, shaft balancing and bearing faults prediction will be carried out using frequency response (FFT).

Objectives

This experiment aims to:
1- Study the importance of shaft balancing and bearing faults in order to avoid undesirable vibrations.
2- Investigate the causes and solutions for bearing faults.
3- Show the difference in the behavior of both balanced and unbalanced system and learn how to identify faults in bearings.

Theory

Unbalancing

Unbalance is caused by the displacement of the mass centerline from the rotor's axis by an eccentricity in the distribution of the rotor mass. In simpler terms, due to centrifugal force, the "heavy" point of a rotor exceeds the centrifugal force exerted by the light side of the rotor and pulls the entire rotor in the direction of the heavy point. Balancing is the correction of this phenomenon by the removal or addition of mass to the component to compensate for centerline error.

Strong radial vibrations at the fundamental frequency will be caused by the unbalance. If the rotor is overhung, then radial and axial vibrations will develop. The vibrations amplitude is proportional to the rotational speed squared.

Unbalances can result in excessive bearing wear, fatigue in support structures, decreased product quality, power losses and adjacent machinery disturbances.

To resolve this problem, and if unbalancing was found to be the reason of the machine vibration, an analysis of the acceleration signal should be performed. By getting the discrete transformation FFT, we can check if the maximum amplitude is occurring at the shaft’s rotational frequency. If this is the case, then the shaft is most likely to be suffering of unbalancing.
The vibrations produced by the unbalance should meet the standards and the acceptance limits, the standards based on the vibration severity depend on:

1) Speed of machinery.
2) Type and size of machine.
3) Expected service.
4) Mounting system.

**Balancing**

There are two general forms of balancing: "Static" and "Dynamic". Static balancing involves installing the component into a balancing machine and measuring the "heavy" point in relation to the centerline while the part is rotating. If the required balance correction is at a single axial point on the rotor the balance is said to be "Single-Plane". Single plane balancing is adequate for rotors which are short in length, such as pulleys and fans. See figure (1).

Dynamic or "Dual-Plane" balancing is required for components or assemblies of significant length. Rotors with some axial length can have two "heavy" points at opposing ends of the component, acting independently on the mass center line. In order to balance the component, both planes must be corrected for center line error. Dynamic balancing is required for components such as shafts and multi-rotor assemblies. See figure (2).

**Bearings**

Rolling element bearings support and locate rotating shafts in machines. The term rolling-element includes both ball bearings and roller bearings, see figure (3) which shows the components of rolling-element bearing. Rolling –element bearings operate with a rolling action whereas plain bearings operate with a sliding action. Bearings may fail because of:
1. Manufacturing errors.
2. Improper Assembly.
3. Loading.
4. Operation.
5. Lubrication.

Figure 3: Rolling-element bearing components

If a bearing is perfectly made, assembled, it will eventually fail due to fatigue of the bearing material. Most modes of failure of bearings involve the growth of discontinuities on the bearing raceway. The vibration of a healthy bearing has low amplitude and looks like random noise. As a fault begins to develop, the vibration produced by the bearing changes.

Every time a rolling-element encounters a discontinuity in its path, a pulse of vibration results. The resulting pulses of vibration repeat periodically at a rate determined by the location of the discontinuity and by the bearing geometry.

The repetition rates are known as the bearing frequencies. More Specifically:

1) Ball-Passing Frequency Outer-race (BPFO) for a fault (defect) on the outer-race
2) Ball-Passing Frequency Inner-race (BPFI) for a fault (defect) on the inner-race
3) Ball-Spin Frequency (BSF) for a fault on the ball.
4) Fundamental Train Frequency (FTF) for a fault on the cage.
The bearing frequencies can be calculated from the bearing geometry using the formulas given below, see figure (4). However, note that the relationships assume pure rolling motion while in reality there is some sliding. Thus, the equations should be regarded as approximate.

![Figure 4: Bearing frequencies](image)

\[
BPFO = \frac{n}{2} f_r \left(1 - \frac{B_D}{P_D} \cos \beta \right) \\
BPFI = \frac{n}{2} f_r \left(1 + \frac{B_D}{P_D} \cos \beta \right) \\
BSF = \frac{1}{2} \frac{P_D}{B_D} f_r \left[1 - \left(\frac{B_D}{P_D} \cos \beta \right)^2 \right] \\
FTF = \frac{1}{2} f_r \left(1 - \frac{B_D}{P_D} \cos \beta \right)
\]

Where:
- \(P_D\): Pitch diameter.
- \(B_D\): Ball diameter.
- \(n\): Number of balls.
- \(\beta\): Contact angle.
- \(f_r\): Relative revolutions per second between inner and outer races.

The simplest way to measure the overall vibration level is to regularly measure the root-mean-square (RMS) average of the vibration level at the bearing housing. This technique involves measuring the root-mean-square (RMS) average of the vibration level over a wide range of frequencies. Measuring acceleration over a range of high frequencies (1 kHz-10 kHz) gives the best results.

The RMS value can be used to calculate the Crest Factor. The Crest factor which is the Peak-RMS ratio of the vibration, can give an earlier indication of bearing failure. The RMS value grows as the number of faults grows, and the peak value grows as the fault grows. See figure (5).

Initially, there is a relatively constant ratio of peak to RMS value. As a fault develops, the resulting short vibrations increase the peak level substantially, but have a little influence
on the RMS level. The peak level will typically grow to a certain level. As the bearing deteriorates, more spikes will be generated, finally influencing the RMS level, giving an indication of the bearing’s failure.

![Crest factor graph](image)

Figure 5: Crest factor

Such measurements can be made using an accelerometer. Measurements are compared with general standards or with established reference values for each bearing. By plotting the measurement results over time, the trend in vibration can be followed and extrapolated to give a prediction of when the bearing needs replacements.

**Experimental Procedures**

**Part 1: Shaft Balancing**

1) Run the “VT001 Software”.
2) From the “Welcome to VT001” screen choose [Run Experiments] button.
3) From the “Vibration Experiments” screen choose Experiment 4: [Shaft Balancing & Bearing Faults].
4) Select the “Balancing” tab.
5) Select the “Frequency Response” tab.
6) Observe the experiment screen, see figure (6).
7) Make sure that the VT001 Vibration Trainer is turned off and the rotor is not rotating. Check the power switch and make sure it is Off. Open the cover and check that there are no screws attached to the disk. If there are, remove them.
8) Close down the cover, and push the power button ON. The shaft is going to move now.

9) Tune the Speed Controller Knob to 4,000 RPM. You should monitor the shaft speed increasing on the Shaft Speed Meter on your Front Panel. See figure (7).

10) Increase the speed up to 6,000 RPM and observe the power spectrum of the acceleration signal. Record your observations. Draw the power spectrum in the chart below (figure (8)).

![Figure 6: Shaft balancing experiment](image)

![Figure 7: Shaft speed meter](image)
11) Press [No Screw] button in order to save the power spectrum data. You can see the data you have saved in the “Saved Data” tab.

12) Turn the VT001 Vibration Trainer Off, and wait until it the motor settles down and stops rotating. DO NOT open the cover while the shaft is still decelerating.

13) Reach for the circular disk and fix in a screw hole; make sure the screw is secured tightly. Close the cover and switch the power ON.

14) Use the speed controller knob to increase the shaft speed to 4,000 RPM.

15) Press the [One Screw] Button in order to save the power spectrum data.

16) Increase the shaft speed gradually to 6,000 RPM while keeping an eye on the power spectrum. What do you observe? Draw the power spectrum in the chart below (figure (9)).
17) Slow down to 3,000 RPM. What does the behavior of the shaft indicate? Why?

**To balance the shaft again, follow the steps as listed below:**

18) Turn the VT001 Vibration Trainer [Off]. Make sure the motor stopped rotating before you open the cover.

19) In which of the holes on the disk should we add a screw to remove the unbalance in our shaft? Why? Check your decision with the lab instructor, and then add the screw to the hole. Turn the VT001 Vibration Trainer [On].

20) Use the speed controller knob to increase the shaft speed to 4,000 RPM.

21) Press the [Two Screws] button in order to save the power spectrum data.

22) Record your observations on the power spectrum chart (figure (10)), have you got something similar to the first power spectrum in this experiment? Explain your answer.
23) Turn the VT001 Vibration Trainer [Off] by using the power button.

**Part 2: Bearing Faults**

1) Run the “VT001 Software”.
2) From the “Welcome to VT001” screen choose [Run Experiments] button.
3) From the “Vibration Experiments” screen choose Experiment 4: [Shaft Balancing & Bearing Faults].
4) Make sure that the VT001 Vibration Trainer is turned off and the rotor is not rotating. Check the power switch and make sure it is Off. Open the cover and check that there are no screws attached to the disk. If there are, remove them.
5) Close down the cover, and push the power button ON. The shaft is going to move now.
6) Select the “Bearings” tab.
7) Select the “Frequency Response” tab, see figure (11).
8) Increase the speed of the motor by adjusting the knob of the controller to 6,000 RPM.
9) Calculate the fundamental frequency.
10) Calculate the bearing frequencies and write them in table (1) below, given that:
    i. The number of the balls in the bearing is 7.
    ii. The contact angle is 0°.
    iii. The pitch diameter is 18mm.
iv. The Ball Diameter is 7mm.

Table 1: Calculated bearing frequencies

<table>
<thead>
<tr>
<th>BPFO (Hz)</th>
<th>BPFI (Hz)</th>
<th>BSF (Hz)</th>
<th>FTF (Hz)</th>
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<tbody>
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11) Show the cursors on the spectrum by clicking the [Show Cursors] button.
12) Observe the frequency spectrum, measure the bearing frequencies and record them in table (2). Compare them with the calculated values in step 10.

Table 2: Bearing frequencies

<table>
<thead>
<tr>
<th>Bearing Frequencies</th>
<th>Calculated Values (step 10)</th>
<th>Measured Values</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPFO (Hz)</td>
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</tr>
<tr>
<td>BPFI (Hz)</td>
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<td>FTF (Hz)</td>
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13) Select the “Bearing Trends” tab.
14) Observe the plot and record the Peak and the RMS values:
   a. Peak Value: ..............
   b. RMS Value: ..............
15) Use the Peak and RMS values calculated in the previous step to calculate the Crest Factor.
16) Monitor the RMS & the Peak values for a couple of minutes, do they change? What do they indicate?
17) To save the experiment, click the [Save] button, and the experiment will be saved on your desktop in a folder named “Vibration Trainer Reports”.
18) Turn the VT001 Vibration Trainer [Off] by using the [Power] button.
19) Click [Return] button to exit the experiment and return to the experiments window.

Discussion and Conclusions

1) In bearing faults part, what does the increase in the RMS value indicates?
2) In bearing faults part, what does the increase in the Peak value indicates?