Fault Diagnosis of Gear by Vibration Analysis

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Abstract - Unexpected production delays cause substantial costs in many branches of industry. A machine consists of many potentially defective elements, such as gears, bearings, shafts etc. During operation, each element contributes to the overall vibration of the machine. Each specific machine element has its own vibration signature. The purpose of machine vibration monitoring is to use the modified vibration signature to detect, localize, diagnose and prognosticate the defective gear so that relevant maintenance can be planned. When a defect e.g., a fatigue crack, appears in an element, e.g., a gear, its signature is modified. The dynamic response of gears is a matter of concern because of noise generation and dynamic loads. The present study is focused on the different modes failures observed in gears which are detected by using vibration based monitoring technique Fast Fourier Transform. A test rig is prepared to carry out the analysis by simulating faults in the gear and generating spectrums of specific faults which are compared with the spectrum of a new gear indicating severity and specificity of fault. The experimental setup has been designed to facilitate generation of spectrum for different pairs of new and defective gears. The modified spectrum from combination of new and defective gears can be attributed to variation from the defective gear, thus identifying the defective gear in the pair. In this paper the empirical data generated by the experimental setup for both new and defective gear for a gear pair used in an automotive transmission is analysed and discussed.

Keywords - Vibration based condition monitoring, Fast Fourier Transform, Modes of Gear failure.

I. INTRODUCTION

Transmission is an important subsystem of engineering systems such as power, automotive gear trains, manufacturing machinery etc. Effectiveness of such systems is dependent on their continued availability through reliability of subsystems. Maintenance of equipment and machines has graduated from breakdown to condition based predictive maintenance. Right information at the right time is crucial aspect of condition-based maintenance strategy in industries. Condition-based maintenance (CBM) consists of real time monitoring of condition of machine systems, identifying faults before catastrophic breakdown occurs. Condition monitoring based maintenance improves the availability by predicting faults facilitating scheduling and planning of maintenance activities, defective components like gears can be withdrawn from service before their condition impairs performance. Gears are critical part of power transmission system. Numerous condition monitoring (CM) and diagnostics methodologies are utilized to identify the machine faults to take corrective action. A number of condition monitoring techniques have emerged such as wear debris analysis, visual inspection through strobe lights, vibration signature analysis, lubricant signature analysis, noise signature analysis, and temperature monitoring, with the use of appropriate sensors /transducers, different signal conditioning, and analyzing hardware /software. The use of vibration analysis as one of the fundamental tools for condition monitoring has been developed extensively over last six decades. Failure mode analysis of gears obtained from published industry data shows the following failures Crack, wear, pitting, corrosion, scoring, plastic flow, tooth breakage. Failure mode analysis of gears obtained from published industry data shows the following failures Crack, wear, pitting, corrosion, scoring, plastic flow, tooth breakage. The paper attempts to collect vibration spectrum of five different simulated gear defects through design of an experimental setup for comparison with the reference signals. A reusable set up was therefore conceptualized and designed for multiple gear fault
simulation. To control speed of the motor it was connected to variable frequency drive (VFD). Accelerometer probes to measure the time domain response were attached magnetically to measure the horizontal and vertical vibration signals generated on the bearing housing of pinion shaft. Accelerometers were used to detect vibration and transmitting the signal to the FFT equipment. Time domain signals of vibration of good and defective gears were obtained through the experimental set up and transformed to frequency domain through FFT. The frequency domain spectrum have been analyzed several patterns have emerged from the analysis of the spectrums obtained in the experiment.

<table>
<thead>
<tr>
<th>Methods of analysis</th>
<th>Thermal</th>
<th>Wear Debris Analysis Spectrometer &amp; Oil</th>
<th>Acoustic Emission analysis</th>
<th>Visual inspection Strobe light analysis</th>
<th>Vibration analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out of balance</td>
<td></td>
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<td></td>
<td></td>
<td>★★</td>
</tr>
<tr>
<td>Misalignment</td>
<td>☆★</td>
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<td></td>
<td></td>
<td>★★</td>
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<tr>
<td>Bent shaft</td>
<td>▲☆★</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Ball Brg</td>
<td>☆★</td>
<td></td>
<td></td>
<td></td>
<td>★★</td>
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<tr>
<td>Journal Brg</td>
<td>☆★</td>
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<td>★★</td>
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<tr>
<td>Mechanical Looseness</td>
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<td></td>
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<td>★★</td>
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<tr>
<td>Mechanical Rubbing</td>
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<td>★★</td>
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<tr>
<td>Noise Cracking</td>
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<td></td>
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<tr>
<td>Leaking valve seats</td>
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<tr>
<td>Gear Damage</td>
<td>☆★</td>
<td></td>
<td></td>
<td></td>
<td>★★</td>
</tr>
</tbody>
</table>

Table 1 Applicability of diagnostic techniques to machine fault.

II. SELECTION AND SIMULATION OF GEAR FAULTS

- WEAR- A surface phenomena in which layers of metals are removed or worn away more or less uniformly from contacting the surfaces of gear teeth.
Wear describes a loss or removal of material of gear flanks. In terms of gear failure, it is more a deterioration of a gear profile, for instance, a damage of a tooth layer. Adhesive and abrasive wear are important modes of wear.

- **Pitting-** ‘A surface fatigue failure which occurs when the endurance limit of the material is exceeded, a failure of this nature depends on surface contact stress and number of stress cycles.’ The condition is characterised by small pits 1/64 to 1/32 in dia. For the analysis the gear used had spalling type of fault which is a sub type of pitting seen in hardened gears. Spalling is a term used to describe a large or massive area where surface material has broken away from the tooth. In through-hardened and softer material, it appears to be a massing of many overlapping or interconnected large pits in one locality. It is similar to destructive pitting except that pits are usually larger in diameter and quite shallow.

- **Fracture-** ‘Failure caused by breakage of whole tooth or substantial portion of tooth this can result from overload or more commonly by, cyclic stressing of the gear tooth beyond the endurance limit of the material.’

- **Corrosion-** It is a surface phenomena observed on the surface of the gear. In some cases when the lubricant or other fluid in the system comes in contact with the surface of the gear material it may rust this is known as corrosion.

- The gears used in this study are spur gears of Kinetic scooters.
- The larger driving gear is connected to motor and has 36 teeth. Two sets of gears used. Material of the gear is SAE8620.
- Smaller gear is the driven gear having 18 teeth. Five sets of gears used. Material of the gear is SAE8620.

### III. COMPONENTS OF TEST RIG

This whole experiment consists of a three phase induction motor and single stage spur gear arrangement.

- Two jaw flexible coupling is use to connect the motor shaft and the driver shaft
- The driver shaft is shaft 1 on which gear is mounted denoted as (G1) which is coupled with the motor by a two jaw flexible coupling.
- The present study the motor is operated at 700 rpm. Therefore speed of the first gear is 700. With a step-up ratio of 1:2, the speed of the pinion shaft 1400 rpm.
- Parallel shaft is shaft 2 on which pinion a small gear is mounted denoted as (P1).
- The assembly of the test rig is as per the requirement of the analysis different faults have to be simulated in gears so that respective vibration spectrums can be generated.
Working and Procedure

As power is supplied the gear start to rotate and mesh with each other the speed of the gear can be varied with the use of Variable frequency drive (VFD). The operational speeds at which the reading has to be taken are 700 rpm and 1400 rpm of shaft 1 as the velocity ratio of gear pair is 2 so the rotational speed of shaft 2 is 1400 rpm and 2800 rpm respectively. There are two sets of gears G1 one is new and another one is worn out with crack on tooth. Similarly there are five sets if pinion P1 one is new and the others are with default as mentioned above. Firstly the new gears are mounted on the shaft and vibration spectrums are generated at 700 and 1400 rpm speed which are denoted as reference spectrums. These spectrums generated will be used as the reference spectrums. New pinion is replaced by a faulty pinion in which dominant defect is wear and spectrum is generated. In this way the procedure is repeated for all the combination of faulty and new gears. The signal is generated by accelerometer which is processed in the FFT setup to generate vibration spectrums. Time domain and frequency domain spectrums are generated which are compared to find that due to fault what amplitude changes are incurred. Accelerometers are placed in horizontal and vertical position of the bearing case to obtain two signals.

Vibration spectrums of new gears are listed below taken at shaft 1 and shaft 2 at rotational speed of 700 rpm and 1400 rpm respectively.
Spectrum is studied by seeing the amplitude of the gear mesh frequency, 1X 2X rpm frequency and the running speed sidebands of the gear mesh frequencies.

Gear mesh frequency (GMF) - angular speed of shaft* No of teeth on gear

\[
GMF_1 = \frac{1}{2} \times GMF \\
GMF_2 = 2 \times GMF \\
GMF_3 = 3 \times GMF
\]

1X rpm - X is the angular speed of shaft
2X rpm - X is the angular speed of shaft

Crest factor – peak value / root mean square value

**IV. ANALYSIS OF SPECTRUM**

Shaft 2 new pinion at 700 horizontal

Shaft 2 new pinion at 700 vertical

Shaft 1 new gear at 1400 horizontal

Shaft 1 new gear at 1400 vertical

Shaft 2 new pinion at 1400 horizontal

Shaft 2 new pinion at 1400 vertical
Table 2 Amplitude values when the condition of gear is new

<table>
<thead>
<tr>
<th>New condition of gear</th>
<th>1X</th>
<th>2X</th>
<th>1GM</th>
<th>2GM</th>
<th>OVERALL</th>
<th>MAX AMP</th>
<th>CF</th>
</tr>
</thead>
<tbody>
<tr>
<td>S 1 700 H</td>
<td>0.7</td>
<td>1.3</td>
<td>0.2</td>
<td>0.05</td>
<td>4.58</td>
<td>2.5</td>
<td>3.80</td>
</tr>
<tr>
<td>S 1 700 V</td>
<td>0.2</td>
<td>1.25</td>
<td>0.3</td>
<td>0.05</td>
<td>2.49</td>
<td>1.45</td>
<td>3.14</td>
</tr>
<tr>
<td>S 2 700 H</td>
<td>0.7</td>
<td>1.2</td>
<td>0.3</td>
<td>0.05</td>
<td>4.81</td>
<td>2.5</td>
<td>4.08</td>
</tr>
<tr>
<td>S 2 700 V</td>
<td>0.7</td>
<td>1.25</td>
<td>0.2</td>
<td>0.1</td>
<td>2.83</td>
<td>0.8</td>
<td>4.83</td>
</tr>
<tr>
<td>S 1 1400 H</td>
<td>2</td>
<td>3.5</td>
<td>0.05</td>
<td>NA</td>
<td>11.74</td>
<td>7</td>
<td>4.62</td>
</tr>
<tr>
<td>S 1 1400 V</td>
<td>1.2</td>
<td>1</td>
<td>0.1</td>
<td>NA</td>
<td>5.72</td>
<td>2.7</td>
<td>4.93</td>
</tr>
<tr>
<td>S 2 1400 H</td>
<td>4</td>
<td>8</td>
<td>0.05</td>
<td>NA</td>
<td>13.47</td>
<td>7.5</td>
<td>3.90</td>
</tr>
<tr>
<td>S 2 1400 V</td>
<td>1</td>
<td>2.8</td>
<td>0.1</td>
<td>NA</td>
<td>7.19</td>
<td>2.8</td>
<td>4.38</td>
</tr>
</tbody>
</table>

From the vibration spectrums generated of new gear, values of the amplitude are noted which are then compared to the amplitude values of the faulty gears to find the deviation in condition and observe change in vibration spectrum.

V. CONCLUSION

- It is observed from the study of various results. There are changes in the vibration spectrum of defective gears as compared to spectrum of reference gear (new) gear.
  The deviation in spectrum of different defective gears is as follows:
- Wear - It is observed by analyzing the spectrums that in most cases at 1X RPM frequency amplitude decreases at 2X RPM amplitude increases or decreases mostly no change or decrease in amplitude is observed at GMF 1 and no change is observed at GMF 2. Change in side band frequencies is observed.
- Pitting - It is observed by analyzing the spectrums that in most cases at 1X RPM frequency amplitude decreases at 2X RPM amplitude decreases, increase in amplitude is observed at GMF 1 and no change or decrease is observed at GMF 2. Change in side band frequencies is observed.
- Corrosion - It is observed by analyzing the spectrums that in most cases at 1X RPM frequency amplitude decreases at 2X RPM amplitude increases mostly no change or increase in amplitude is observed at GMF 1 and amplitude decreases or no change is observed at GMF 2. Change in side band frequencies is observed.
- Crack Gear - It is observed by analyzing the spectrums that in most cases at 1X RPM frequency amplitude increases at 2X RPM amplitude increases, mostly no change or decrease in amplitude is observed at GMF 1 and no change or increase and decrease in amplitude is observed at GMF 2. Change in side band frequencies is observed.
- Crack Pinion - It is observed by analyzing the spectrums that in most cases at 1X RPM frequency amplitude increases at 2X RPM amplitude increase or decrease in amplitude, increase in amplitude is observed at GMF 1 and amplitude decreases or no change is observed at GMF 2. Change in side band frequencies is observed.

REFERENCES

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