Review on Fault Identification and Diagnosis of Gear Pair by Experimental Vibration Analysis

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***Abstract*—Gears are the most important mechanisms used in power transmission systems. Effective transmission is possible if the pairs don't have any sort of disorder in manufacturing and assembling. Some of the problems may cause improper working of gear pair or may create more noise and vibration. Some of such sources of vibration are – deviations from ideal gear tooth profile, teeth manufacturing errors, deviations in the mesh angle, surface roughness of the gears, misalignment and looseness of the gears, gear eccentricity, wear of meshing surfaces and localized gear damage such as tooth wear, scoring, chipping and pitting. In this review paper, the details regarding fault identification and fault diagnosis by vibration analysis are discussed in brief.**

***Keywords*—fault diagnosis, condition monitoring, gear pair, vibration analysis.**

I. Introduction

Gears are the most important mechanisms used for transmitting power, which plays an important role in many sort of machineries. Smooth operation and high efficiency of gears are necessary for the normal running of machineries. Therefore, gear damage assessment is an important topic in the field of condition monitoring and fault diagnosis.

Effective transmission is possible if the pairs don't have any sort of disorder in manufacturing and assembling. Some of the problems may cause improper working of gear pair or may create more noise and vibration. Some of those problems are as follows:

1. Deviations from ideal gear tooth profile,
2. Gear teeth manufacturing errors,
3. Deviations in the mesh angle,
4. Surface roughness of the gears,
5. Misalignment and looseness of the gears,
6. Gear eccentricity,
7. Wear of meshing surfaces,
8. Localized gear damage such as tooth wear, scoring, chipping and pitting, etc.

Techniques such as wear and debris analysis acoustic emissions require accessibility to the gearbox either to collect samples or to mount the transducers on or near the gearbox. Vibration analysis is one of the most important techniques in condition monitoring techniques that are applied in real life. Most of the defects encountered in the rotating machinery give rise to a distinct vibration pattern and hence mostly faults can be identified using vibration signature analysis techniques. There are basically two types of vibration analysis are widely used such as – time domain and frequency domain analysis. Also there are many more vibration signal processing techniques are available for analyzing the data obtained in actual experimentation. Some of those techniques are as follows- time waveform analysis, analysis of amplitude modulation, cepstrum analysis and time synchronous analysis. Some time the analysis is done with the help of some numerical diagnostic techniques such as RMS value, spectral kurtosis analysis and crest factor analysis. Some of these techniques are discussed in this paper in brief.

FFT Analyzer is one of the instrument is widely used for vibration analysis of various vibrating structures and machineries. It is an instrument used for converting time domain data into frequency domain data. Also this instrument used for detecting the vibration signals and for interpretation of such data in a useful format or graphical view. From literature it is observed that it is possible to use the FFT analyzer for fault diagnosis and condition monitoring of various machineries consisting of gear pairs.

In this paper the information related to experimental setup as well as the instruments required for performing the experimental vibration analysis are discussed in detail.

II. Objectives

1. To study the methods used for fault identification and fault diagnosis.
2. To study instruments used for experimental vibration analysis of a gear pair.
3. To study various numerical treatments and signal analysis techniques used for fault diagnosis of a rotating object.
4. To study actual flow path to be followed for the experimentation.
5. To study the comparative method for fault identification.

III. Methods used for fault identification and diagnosis

There are several methods available for fault identification and diagnosis analysis of rotary machine components, but some of the important methods are

1. Experimental Vibration analysis (time domain or frequency domain/spectrum analysis),
2. Acoustic Method (Acoustic Emission Technique),
3. Finite Element Analysis (Simulation),
4. Thermal Analysis (Temperature measurement),
5. Wear debris analysis (Spectrometer and oil),
6. Visual Inspection (Strobe light analysis).

There are two methods: (1) Experimental Vibration Analysis and (2) Acoustic Emission method, which are highly suitable and reliable for condition monitoring or fault identification. In ***experimental vibration analysis***, vibration signatures from transducers are recorded and analyzed for any sort of fault identification in rotating machineries by constructing an experimental setup.This technique can be applied for identifying almost all types of faults in any vibrating structure. Further details regarding this analysis are discussed in next chapter. ***Acoustic Emission technique*** is also based on the same process, but rather than of recording and analyzing the vibration data, acoustic data like sound level, sound power and sound intensity are measured and analyzed (by using microphone instead of vibration transducers).It is observed from literature that acoustic emission technique is generally suitable for identification of faults like faults in journal bearings, looseness between mating parts and rubbing of parts, also it is more sensitive to crack propagation.

Finite Element Analysis (FEA) is also one of the techniques nowadays used for identifyingbehavior of rotating or vibrating structures. This technique can be applied for validating the results obtained from the experimentation. In this method, simulation is used for analysis and required results are obtained by applied the loading condition as applied in the actual condition. This method is also suitable to identify the natural frequency, mode shapes and also suitable for acoustic analysis of any vibrating structure.

Thermal analysis (Temperature measurement)is one of the methods which can be used for identifying the severity of the fault in mating parts by measuring the temperature with the help of temperature measuring devices like thermocouple. This sort of technique is applicable as fault diagnostic technique for some of the faults like bending of shaft, misalignment of rotary components, faults in ball and journal bearings.

Wear debris analysis is also a simple technique capable of identifying the faults like rubbing, chipping, gear damage, pitting of mating parts. Also the severity of the fault can also be identified simply by observingthe amount of debris material present in the used lubricating oil collected in the sump. This technique is only capable to identify the faults created in the mating parts.

IV. Experimental Vibration Analysis

One of the most efficient, suitable and reliable technique used for fault detection and diagnosis is an experimental vibration analysis, which is itself a self valedictory technique. This method is widely used for various vibrating structures but most probably it is used for rotating machineries. There are various signals which can be obtained in this technique for analysis. Those are explained later.

This technique is based on the analysis of vibration parameters measured with respect to time or frequency or rotational angle. These vibration parameters like displacement, velocity or acceleration are measured by various transducers. The transducers are placed on the proper location of vibrating structure for accurate measurement. Further these transducers are connected to the FFT analyzer or display units, which will convert or display the output waveform or signal. FFT analyzer is connected to the computer with software installed for proper analysis of the recorded data and also for storage. The details regarding the experimental vibration analysis are explained below:

1. *Instruments Required*

For setting up the experimental setup and for vibration analysis some of the instruments are necessary. The instruments required for analysis are discussed below:

1. *FFT Analyzer*
   This instrument is used generally for measuring, recording and converting the time domain data into frequency domain data. FFT is Fast Fourier Transform. FFT Analyzer is an intermediate between transducer and computer. There are many sort of portable FFT analyzers are also available.

Fig. 1 FFT Analyzer

Fig. 2 Transducer (Accelerometer)

2. *Transducer*
   Transducers are the instruments which are converting the physical quantities (like displacement, velocity or acceleration) into electrical quantities. Depending on the vibration parameter to be measured, type of transducer is selected. Mounting of transducer is also important consideration while doing analysis. There are several methods of mountings such as magnet mounting, adhesive mounting, stud mount, etc. Other parameters such as dimensions, location, sensitivity, effectiveness and reliability of the transducer are also the responsible for selection of transducer.

3. *Motor/ Drive Unit with dimmerstat*
   Generally the speed in the machineries where the gear pairs are used for power transmission is greater than 100 rpm. So it is essential to provide the driving unit for experimental setup. Three phase induction motors can be used as those are capable of generating high speed and torque value is also as per requirement. The speed of the induction motor can be varied with the help of an instrument known as dimmer stat.

Fig. 3 Induction Motor

Fig. 4 Rope Brake Dynamometer

4. *Dynamometer*
   Dynamometer can be used for applying the amount of torque on the rotating shaft with the help of a pulley in case of a rope brake dynamometer. Normally rope brake dynamometer can be used for applying a required torque, as it is more easy for manufacturing and cost effective.

5. *Coupling*
   Coupling is an element used for connecting two shafts of may be same of different diameter. Power coming shaft of motor can be given to the gear pair in the experimental setup by using a connecting element known as coupling.

6. *Base Frame*
   Construction base frame will decide overall performance of the experimental setup. The base has to be more rigid, such as it can be capable of sustaining the whole weight of the components used in the setup. Also it has to be taken into account that the phenomena known as resonance may not occur frequently in the whole setup.

2. *Experimental Procedure*

Nowadays it is much more essential to perform the condition monitoring of the rotary machineries in some of the applications such as power plants, various industrial machineries, etc. Also sometimes it becomes necessary to check the severity of the problems and initiation of the fault as a part of precaution. Further the remedies can be applied to avoid the failure or heavy maintenance. It is a simple technique to check the initiation or severity of faults occurring in the machineries. The guideline or flow process is given and can be used to perform the condition monitoring of any of the system where rotary machineries are mostly used for power transmission.

1. Formation of experimental setup (in case of the individual parts testing/sometimes machinery may be used as an experimental setup) for vibration analysis of gear pair by making an arrangement for replacement of healthy gear pair by faulty gear pair.
2. Conducting an experiment for getting the vibration signatures by locating the sensor/transducers at various locations on the experimental setup for healthy machinery.
3. Again conducting an experiment after a scheduled time period for getting the vibration signatures by locating the sensor/transducer at same locations on the experimental setup.
4. Recording, observing and comparing the vibration signature will give a definite conclusion.

The general flow path to be followed for a gear pair is given below in Fig. 1. In this flow diagram, it can be observed that the motor is a driving unit and the gear pairs such as healthy and faulty gear pairs are driven one by one. The coupling is the connecting part, which transmits the power from motor to the gear pair. Tachometer is the measuring instrument used for measuring speed and dynamometer is used to apply the load and to measure the torque generated. Accelerometer is the transducer used for measuring and transmitting the vibration data (i.e. acceleration) to the FFT Analyzer. FFT Analyzer is the instrument used for converting the time domain data into frequency domain data, as sometimes it becomes more complicated to analyze the time domain data. Computer with software installed, will show the data in terms of graphs and curves. So it becomes easy to analyze. The vibration signature monitoring and analysis technique used is time and frequency domain analysis. Here, the statistical technique used for analysis is RMS value comparison. The faults can be created for testing purposes same as created in actual working conditions. Various techniques are discussed in further chapter.

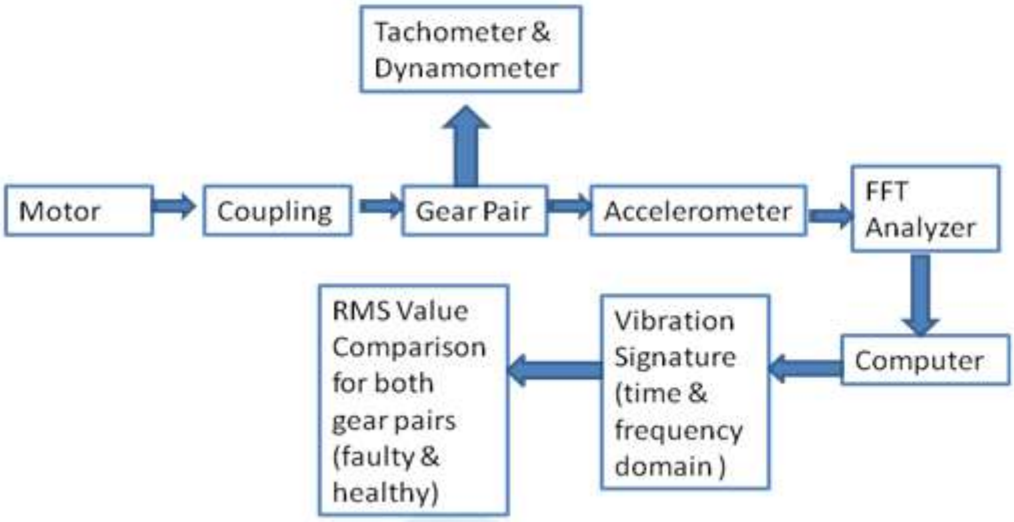

Fig. 5 Flow Diagram for Fault Identification

3. *Vibration Signature Monitoring and Analysis Techniques*

Condition monitoring and fault diagnosis is based on the vibration signature monitoring of the machinery. There are several techniques used for monitoring and analysis. Basically two techniques viz. time domain analysis and frequency domain analysis are more popular and reliable for condition monitoring with the help of frequency analyzers. Some of the techniques are reliable for particular faults identification. It is sometimes becomes difficult to use a common technique for every fault diagnosis. So it becomes necessary to use appropriate technique for proper diagnosis. Various techniques are enlisted below.

1. *Time Domain Analysis*
2. *Frequency Domain Analysis/Spectrum Analysis*
3. *Analysis of amplitude modulation*
4. *Cepstrum Analysis*
5. *Orbit Analysis*
6. *Spectrum Cascade/Waterfall Analysis*
7. *Wavelet Analysis*

Time Domain Analysis is the technique in which the graph is plotted as vibration parameter measured versus time. The vibration parameters such as displacement, velocity or acceleration are taken on y-axis and time parameter is taken on x-axis. Generally time domain analysis is done by using the instruments like oscilloscope, data recorder, data acquisition system, etc.In some cases, it becomes difficult to identify the fault just by comparing the time domain graphs. General applications where the time domain analysis is preferred are unbalance, bearing outer race fault, looseness, etc.

Frequency Domain Analysis is one the most reliable, best suited and most widely used method for fault identification. In this analysis, frequency domain data is used for diagnostics. The mathematical transformation of the time domain data into frequency domain is done with help of frequency analyzer like FFT analyzer where FFT algorithm is used. This technique can be used for identifying around 85% of the mechanical problems.

4. *Statistical/ Numerical Treatments for vibration analysis*

There are some indices which are helpful in deciding that the system possesses the faults. These indices for healthy and faulty gear pairs/machineries can be measured and compared with reference to some baseline for identifying the initiation or severity of the faults. These indices are also known as statistical descriptors of vibration signals measured. Some of these statistical descriptors are peak, mean, RMS, crest factor, skewness, kurtosis, K-factor, Impulse Factor, Shape Factor. It becomes easy to plot the graphs of any reliable descriptor with respect to time parameter in both the conditions viz. healthy and faulty condition, variation in the graphical picture of the parameter will give an indication of fault. These numerical treatments are discussed in detail below:

1. *Peak Value* (x_{max})
   This is the maximum value of the vibration parameter without any considerations of time or frequency. This is one of the features used for fault diagnosis. The vibration parameter may be displacement, velocity or acceleration.

2. *Mean Value* ($\bar{x}$)
Mean value is nothing but it is an average value of the vibration parameter measured. Large variations from mean value will indicate a large fluctuation in working from normal working condition. Mean value can be calculated by using the formula given below

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

Where, x_i represents the *i*th value of the discrete-time signal and N be the number of measurement samples.

3. *Root Mean Square (RMS) Value*
It is most relevant parameter used for identification of fault severity. It is also a parameter used for comparison of the vibration parameter for healthy and faulty gear pair. In the flow diagram give above the RMS value is considered as a statistical method for fault diagnosis. RMS value can be written mathematically as follows

$$x_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2}$$

Where, x_i represents the *i*th value of the discrete-time signal and N be the number of measurement samples.

4. *Crest Factor*
The crest factor is defined as the ratio of the peak value to the RMS value of a signal(peak-to-RMS-ratio). It is a dimensionless quantity.A typical vibration signal from a machine with imbalance, but no other problems will have a crest factor of about 1.5. As the faults like wear grows up in the system, the value of crest factor goes on increasing. Crest Factor is used generally in bearing diagnostics as given in the literature.

$$Crest\ Factor = \frac{x_{max}}{x_{RMS}}$$

5. *K Factor*
K factor is defined as the product of the maximum (peak) value and the RMS value of the signal. This value goes on increasing with the faults.

$$\mathrm{KF} = x_{max} \times x_{RMS}$$

6. *Impulse Factor*
It is defined as the ratio of the peak value to the mean value of the time signal and may be mathematically expressed as

$$IF = \frac{x_{max}}{\bar{x}}$$

7. *Shape Factor*
It is defined as the ratio of the RMS value to the mean value of the time signal.

$$SF = \frac{x_{RMS}}{\bar{x}}$$

8. *Kurtosis*
A normal damage has a kurtosis value of 3. It is the parameter which is based on the working condition of the gears in mesh. It is possible to detect the fault by comparing the kurtosis values.

$$\text{Kurtosis (K)} = \frac{1}{\sigma^4}\sum_{i=1}^{N}\frac{(x_i - \bar{x})^4}{N}$$

Where, N = Number of samples taken within the signal,
σ^4 = Variance Square,
$\bar{x}$ = Mean Value of samples,
x_i = Individual Value.

V. CONCLUSION

It can be concluded that condition monitoring technique by vibration analysis can be used for fault diagnosis of any vibrating machinery. Also by measuring and analyzing the vibration of a machine, it is possible to determine both the nature and severity of the defect. Hence the prediction of failure point or useful life is possible. Each technique, except synchronous averaging analysis is capable of damage identification and damage severity evaluation. Time waveform analysis is very efficient in damage identification. Also it can be concluded that cepstrum technique is efficient for detecting changes not easily notable in the spectrum and also suitable for earlier damage identification. Time synchronous averaging is very effective in damage localization for a single shaft. Also it can be concluded from the literature available that it is possible to use the RMS values of rotational vibration acceleration to evaluate faults severity assessment.

This technique of condition monitoring and fault diagnostic is easy and cost effective with an additional benefit such as it is a non-destructive method of inspection.

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