CHAPTER 2

AC INDUCTION MOTOR AND VIBRATION SIGNAL

This chapter presents the basic knowledge of AC induction motor and vibration signal. The main knowledge of AC induction motor is taken from Fitzgerald [8] while the knowledge in vibration is taken from various sources as referred in each section.

2.1 Introduction of Motor

Motor plays the important part in today's industry. It is used to transform the electrical energy into the mechanical energy. In every manufacturing plants, they use motor in their processes ranged from small and high precision to the large size with high output.

Classification of motor can be done by size, type, characteristic, speed controller, and so forth. If we classify it by input energy supply and characteristic, major types of motor will be AC induction motor, AC synchronous motor, and DC motor.

In general manufacturing plants, AC induction motor gain high popularity since it requires less maintenance than DC motor though its precision still come after

DC motor. Moreover, can drive high range of applications e.g. pumps, fans, blowers and conveyers etc. The most important reason, especially in outdoor area, is it employs alternating current which is the main electrical system in Thailand; it can use electrical power directly from the supply without any special transformation, except in variable speed control.

2.1.1 Structure of AC Induction Motor

The motor consists of stationary and rotating components which are called stator and rotor. The rotor lies on stator through 2 side bearings.

The stator consists of iron core and stator winding. The iron core functions for

1) outer casing of motor protecting any damage from outside mechanical force and contamination from foreign particles (indicated as Index of Protection : IP),
2) core for stator winding and
3) path for magnetic field created from stator winding current.

The stator core is constructed from the laminated iron plates, which is designed to minimize the iron and eddy current loss.

The stator winding comprises of three circuits for three-phase electrical AC supply. The figure illustrates below.

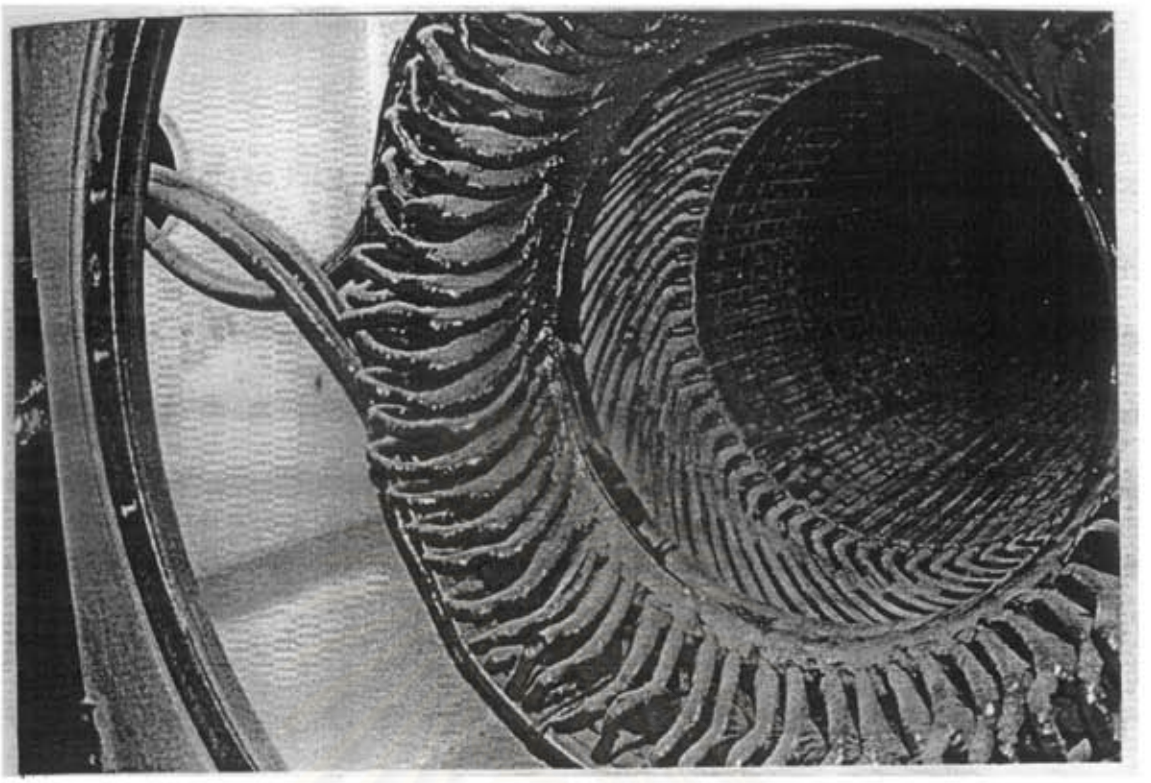

Figure 2.1 Stator of AC induction motor

Source: Independent Power Producer of Thailand.

Pattern of stator winding is similar to synchronous motor stator winding. The stator could be designed for 2 poles, 4 poles or any number times even number of poles.

Two types of rotor in three-phase induction motor are squirrel cage and wound rotor types. Squirrel cage rotor is mostly used in small size induction motor while the wound rotor is popular in larger size. The wound rotor is set of conductors winding along the rotor that must have the same number of poles as stator winding pole. Its conductor end will connected to slip-ring brush. Slip ring can be either connected directly to the supply or connected via the starter in order to reduce the starting torque.

2.1.2 Rotating Magnetic Field

According to Fitzgarald [8], electricity supplied in the stator side will produce rotating electromagnetic field, which will induce the current flow in the rotor bar. The shorted ring on both side of rotor and designed winding route will be induced by rotating electromagnetic field to generate torque, which turn the motor to run. The force of rotating magnetic field can be explained by the mathematics below. Please noted that I is for current while F is for force. The parameters a, b, and c are for three phases system.

$$Ia = I \cos(wt)$$

$$Ib = I \cos(wt - 120)$$

$$Ic = I \cos(wt + 120)$$

$$|Fa| = F \cos(wt)$$

$$|Fb| = F \cos(wt - 120)$$

$$|Fc| = F \cos(wt + 120)$$

$$Fa = |Fa|\, I + 0\, J$$

$$Fb = |Fb| \cos(-120)\, I + |Fb| \sin(-120)\, J$$

$$Fc = |Fc| \cos(120)\, I + |Fc| \sin(120)\, J$$

$$Fa = F \cos(wt)\, I + 0J$$

$$Fb = -0.5\, F \cos(wt-120)\, I - 0.866\, F \sin(wt-120)\, J$$

$$Fc = -0.5\, F \cos(wt+120)\, I + 0.866\, F \sin(wt+120)\, J$$

By trigonometry theory, Fb and Fc will be

$$Fb = -0.5\,F[\cos wt \cos 120 + \sin wt \sin 120]\,I$$
$$- 0.866\,F\,[\cos wt \cos 120 + \sin wt \sin 120]\,J$$
$$= [\,0.25\,F \cos wt - 0.866/2\,F \sin wt\,]\,I + [0.866/2\,F \cos wt - 0.75\,F \sin wt]\,J$$

$$Fc = -0.5\,F[\cos wt \cos 120 - \sin wt \sin 120]\,I +$$
$$0.866\,F\,[\cos wt \cos 120 - \sin wt \sin 120]\,J$$
$$= [\,0.25\,F \cos wt + 0.866/2\,F \sin wt\,]\,I +$$
$$[-0.866/2\,F \cos wt - 0.75\,F \sin wt]\,J$$

$$F = Fa + Fb + Fc$$
$$= 1.5\,F \cos wt\,I - 1.5\,F \sin wt\,J$$
$$= 1.5\,F\,[\cos wt\,I + \sin wt\,J]$$

F is the total magnetic force, which is the function of time and phases. So the three phase current could create the rotating fix-magnitude magnetic field in clockwise direction with the same speed as supplied current frequency, this we usually say synchronous speed. The number of pole would result in faster speed of magnetic field.

The rotating magnetic field is the key in rotation of induction motor. It creates the mechanical force or electromagnetic force across the air gap between stator and rotor. The output of induction motor will depends on the magnitude of electromagnetic force. If the supplied power is not uniform or imbalance, the electromagnetic force

will be imbalance, which can lead to the failure of the motor. The discussion of this matter will be done in later section.

2.1.3 Mechanical Force and Slip Frequency

By Faraday's Law, the change of magnetic field on rotor bar from rotating magnetic field creates the electromagnetic force (emf) on rotor. Since the rotor bar is close loop itself, the current would be created on the rotor bar. From right-hand rule, the current crossing the magnetic field could establish the mechanical force which turn the rotor. The rotor would turn in the same direction as the rotating magnetic field turns but at different speed.

After the rotor could rotate by such mechanical force, the relative magnetic field changed on rotor bar will decreases. Then the emf and current on rotor bar will decline. Anyhow the rotor angular speed never meets that magnetic field speed otherwise the emf and current on rotor bar as well as mechanical force would be zero and rotor could not keep on turning anymore. There would be always little speed different between rotor speed and magnitude field speed called speed slip. The calculation of slip frequency is shown below.

slip frequency = synchronous speed – actual speed

If the rotor shaft are coupled to any type of load, i.e. fan, pump, blower, and forth,. such load mass would reduce the rotor speed. Then the relative speed between rotor and magnetic field would increase. The emf and rotor current are consequently

increased. And mechanical force would also increases. Since the higher rotor current with higher speed slip create the higher back emf on stator winding the stator winding current is then higher. So not only that the higher speed slip would indicate the higher load, but also the higher stator current would be.

Anyhow with limit of windings current limit, magnetic field saturation on core limit, the motor is designed to run for full load at slight speed slip practically 5% of synchronous speed. Slip frequency is another frequency that can point out to the failure of motor. It will be discussed later in spectrum analysis session.

2.1.4 Failure Parts of Motor

The failure can occur either on the rotating element or non-rotating element. The undesired result is that motor can not rotate or can not drive the load. The most frequent failure on rotating part is on rotor and support bearing. Bearing will be broken down from many reasons such as lack of proper lubricating, for instance.

However, most of those failures can be pointed out by vibration signal.

2.2 Vibration

Vibration signal occur when particle in mechanical part vibrate or move simple harmonically. It is the behavior of a machine's mechanical components as they react to internal or external force [SKF, 21]. It can be measured with various type of unit: mm,

mm/s, mm/s^2, and forth. Since most machinery problems show themselves as excessive vibration, the vibration signal can be used as one type of indicator to indicate the probable failure of the machine in the future.

2.2.1 Vibration monitoring

Since the vibration can indicate condition of machine, it should be monitor to see whether the machine is operating in normal condition or not. Then, the vibration value is analyzed by vibration analysis.

2.2.2 Vibration analysis

There are many ways to obtain and display vibration data. The obtained vibration value will be analyzed by experienced human expert. The vibration data then can be interpreted to pinpoint the failure part. According to Corvib [33], the benefit of vibration analysis can be seen as below

- ✓ Less Downtime
- ✓ Less Spare Parts Inventory
- ✓ Better Management Time Allocation
- ✓ Less Overhaul-Overkill
- ✓ Longer Production Runs
- ✓ Better Quality
- ✓ Less Downtime
- ✓ Less Spare Parts Inventory

- ✓ Better Management Time Allocation
- ✓ Less Overhaul-Overkill
- ✓ Longer Production Runs
- ✓ Better Quality

Vibration analysis is not the only way to diagnose failure of motor, but it is one of the most popular technique because its effectiveness. Principle of vibration analysis is finding the source of vibration signal and deciding the level of severity before making a decision to take correcting action. It can be used along with another technique for more precise failure diagnosis.

2.2.3 Source of vibration

Vibration may come from either the external or internal motor. As mention that it can point out the failure part, it will be used as an indicator to prove whether the taken action is effective or not. If the taken action is effective, amplitude of the vibration will decrease. Moreover, decreasing of vibration's amplitude prove that the action is taken correctly to the source.

Lawrie [15] point out that many causes of excessive vibration that are detrimental to motors and machinery. They are included in the following list.

- ➢ Imbalance
- ➢ Bad bearings.

- Improper lubrication.
- Misalignment.
- Bent or worn shafts.
- Badly worn gears.
- Worn or misalign couplings.
- Worn belt pulleys, old belts; improper tensioning of belts, misalignment of belt drives.
- Expansion or contraction of piping or related metal parts
- Improper foundation mass, grout or bracing.
- Overload (in some instances, underload or cavitation in pumps).
- Static electricity and stray currents.
- Electrical imbalance

The assumption of vibration source has to be set before taking any corrective action. The higher experience, the more accurate assumption.

2.2.4 Measuring Vibration Signal

Vibration signal can be obtained via the data collector, which have various models in many brand names. However, it can be categorized in two major types; overall value and vibration spectrum.

Mostly, the data collector used for collecting overall value have small size. For example 'picolog', the overall value collector from SKF, have size smaller as cellular phone. Whilst, the instrument for vibration spectrum collector is larger.

2.2.4.1 Equipment for vibration analysis

The equipment used for collecting and analyzing vibration signal can be seen in figure below

Figure 2.2 picture of vibration analyzer [4, p.73]

Generally, the equipment for collecting vibration data can be divided into two groups

1. The portable time domain analyzer: this equipment can give the overall value of vibration signal. Mostly, its shape is small as palm portable.

2 Frequency or spectrum analyzer: more function than time domain analyzer can be found in this type. Its size is different by various brands; it can be either palm holding shape or like portable laptop computer. Its screen can show spectrum shape of vibration signal.

2.2.4.2 Points to measuring

Generally, AC induction motor that is horizontally mounted has two support bearings located on the driving-end side and the non-driving-end side. The point of measurement is on those two sides with three planes; vertical plane, horizontal plane, and axial plane. Therefore, the measurement should be done on six points as shown below.

1. horizontal driving-end
2. vertical driving-end
3. axial driving-end
4. horizontal non-driving-end
5. vertical non-driving-end
6. axial non-driving-end

For vertical mounting induction motor, the horizontal and vertical axis will be radial axis. The points of measuring will be two points 90 perpendicularly on radial plane and one point on axial plane at each supportive bearing. However, some special design of induction motor and its load may not allow the user to take all six measuring points. In that case, the two main points for measurement will be one point on axial

plane and one point on radial plane. The figure below taken from ISO 10816-1 [10] presents the point of measurement.

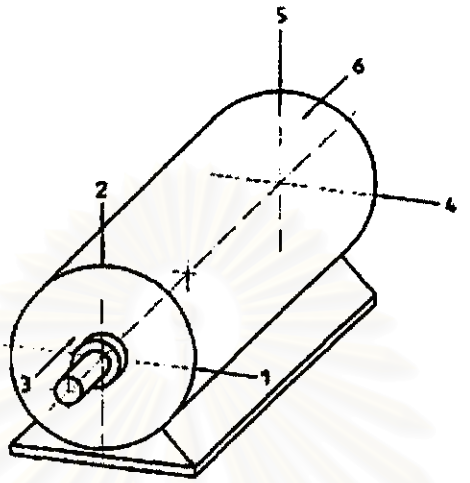

Figure 2.3 measuring points on horizontally mounted machine

Source ISO 10816 [10]

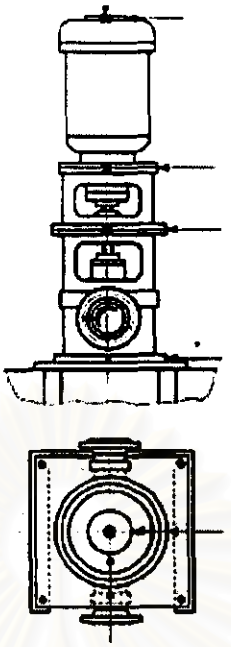

Figure 2.4 measuring points on vertically mounted machine

Source ISO 10816 [10]

2.2.5 Amplitude

Amplitude is the size of vibration signal. It will be used to determine the severity of failure. The higher amplitude, the higher severity of failure. The amplitude of vibration signal, normally, is the peak value while the overall value is mostly measured in r.m.s. value.

2.2.6 Frequency

Frequency is the measuring of signal per one unit of time period. In vibration analysis, the frequency of vibration signal can indicate the potential source of vibration signal, called failure frequency. Each component part in the machine has its

own natural frequency at a certain value. Therefore, certain type of failures will occur at the certain frequencies.

2.2.7 Spectrum analysis by Fast Fourier Transform

"Joseph Fourier submitted a paper in 1807 to the Academy of Sciences of Paris. The paper was a mathematical description of problems involving heat conduction, and was at first rejected for lack of mathematical rigour. However, it contained ideas, which have developed into an important area of mathematics named in his honor," [30]

When detect the vibration signal from rotating equipment like AC induction motor, the obtained signal will be sinusoidal characteristic. Theoretically, when the machine run at constant speed, the signal will be pure sinusoidal wave form at running frequency. However, the realistic pattern of any wave form generated from rotating machine is combination of many sinusoidal waves at different frequency. Those sources of frequency may come from harmonic of running speed, or another sources of vibration indicated some failure. Hence, the resulted is non-pure sinusoidal wave form of vibration signal.

On time domain, the wave form is distorted pure sinusoidal wave form. Its shape depends on the combined frequency. This wave form can only present the overall value or integrated area under the curve. In case of detecting failure, the overall value can tell only the severity level of the signal.

Therefore, in order to digest each frequency component of wave form, the technique needed is Fast Fourier Transform.

Fast Fourier Transform or FFT is the mathematical technique used to converted time domain wave form to frequency domain wave form. Spectrum analysis, another technique to diagnosis machine failure, use Fast Fourier Transform to display the signal amplitudes as a function of frequency.

2.2.8 Vibration Severity

Generally, the severity level of any machine can be defined as rough two steps; good level and bad level, or acceptable level or unacceptable level, for instance. However, for predicting the machine failure, alarm level or warning level to warn operator or engineer before the failure occurs is needed. Hence, the severity level should more categorized.

From manual of SKF's vibration analyzer, the severity level is categorized into four levels as shown below

1. Good: the vibration is in the good status.
2. Satisfactory: the vibration grow up, but it is still be acceptable
3. Unsatisfactory: the vibration level exceeds the normal level.
4. Unacceptable: the vibration level is extremely high. It is unacceptable.

The four level of severity is generally used by different name, but the concept of each level is the same. According to the ISO 10816 [10], the four levels are

named as level A, B, C, and D. The size of magnitude is different by size of motor. Table B1 of ISO 10816-1 is shown in Table 2.1 below.

<table>
<tr><th>R.m.s. vibration velocity mm/s</th><th>Class I</th><th>Class II</th><th>Class III</th><th>Class IV</th></tr>
<tr><td>0.28</td><td rowspan="3">A</td><td rowspan="3">A</td><td rowspan="4">A</td><td rowspan="4">A</td></tr>
<tr><td>0.45</td></tr>
<tr><td>0.71</td></tr>
<tr><td>1.12</td><td rowspan="2">B</td></tr>
<tr><td>1.8</td><td rowspan="2">B</td></tr>
<tr><td>2.8</td><td rowspan="2">C</td><td rowspan="2">B</td></tr>
<tr><td>4.5</td><td rowspan="2">C</td><td rowspan="2">B</td></tr>
<tr><td>7.1</td><td rowspan="5">D</td><td rowspan="2">C</td></tr>
<tr><td>11.2</td><td rowspan="4">D</td><td rowspan="2">C</td></tr>
<tr><td>18</td><td rowspan="3">D</td></tr>
<tr><td>28</td><td rowspan="2">D</td></tr>
<tr><td>45</td></tr>
</table>

Table 2.1 Vibration severity from table B1 of ISO 10816

In vibration spectrum, it is possible to find many of peaks at random frequency. Sometimes, the user may be misleading to consider high noise level as a peak of spectrum. By human experience, such a problem can be eliminated. The human experts in vibration diagnosis can categorize whether the peak is exceeded the severity level or not.

Nevertheless, for non-experience analyzers, the properly level of peak's amplitude can be guided by following instruction. [7]

For in ***service motor***, the amplitude should not be higher than 0.100 inch per second

For new or ***rebuilt motor***, the amplitude should not be higher than 0.050 inch per second

For ***precision machine tools***, the amplitude should not be higher than 0.025 inch per second

However, to determine the level of severity, the characteristic of machine and its environment should be considered. The same level of amplitude of two machines at different environment may give the different severity.

2.2.9 Other Techniques for analysis

2.2.9.1 Oil analysis: like grease, oil is used for lubricating the rotating parts of the machine. It can be used together with vibration analysis. TROYER [24] conducted the research at Monash University, Melborne, Australia. He found that the correlation between oil analysis and vibration analysis is generally very good. The conclusions as follows

1) Both techniques are required to control the root causes of machine failure.
2) Often, one technique serves as the leading indicator of machine failure while the other serves as the confirming indicator.
3) Oil analysis is generally stronger in detecting failures in gearboxes, hydraulic systems and reciprocating equipment.
4) Vibration analysis is generally stronger in detecting failures in high-speed journal bearing systems.
5) Vibration analysis is often better at localizing the point of failure depending on the application.
6) Oil analysis is often stronger in determining which wear mechanism is inducing failure.

7) Both techniques are required to effectively determine the root cause of failure.
8) Correlation between oil analysis and vibration analysis is very good, but there are contrary instances.

2.3 Diagnosis

Diagnosis can be defined as the process to find the source or reason of machine failure. When the symptoms shows that the machine has a discrepancy between normal machine status and current status, the diagnosis task should be done.

When diagnosis vibration signal from the machine, three diagnosis strategies will be selected depending on the situation. They are shown as below.

2.3.1 High level of reasoning diagnosis

In this diagnosis strategy, the deep knowledge of machine structure and its characteristic are used to find out the source of failure symptom. Assumptions will be set based on the reasoning and will be proved by solid data.

2.3.2 Diagnosis from experience

Human expert often use their past experience based on statistical intuitions for diagnosis the failure of machine. The deep knowledge of machine structure and

characteristic are seldom referenced. A successful of this strategy depend heavily on the experience of human expert rather than from theoretical reasoning. Hence, the result may be inaccuracy or even fault. However, it can find the source of failure more practically in some cases.

2.3.3 Combination strategy

Both of the two strategies above has its good points. Hence, the best way for diagnosis machine failure is use the combination of them. It will be more effective and efficient since the good points are bring altogether. However, it is difficult to classified whether the human experts are using their experience or high level reasoning knowledge.

Practically, the combination strategy is employed by human experts. Their past experience will be used first. Then the deep knowledge of machine structure and characteristic will be used to confirm their diagnosis result. Sometime, past experience can not be used as the first step; especially in the new experience of failure.

2.4 Literature Survey and Internet Sources

Apart from the literature referenced in above sections, there are some related literatures related to the vibration analysis. They are shown as below.

Furthermore, with today's technology, the Internet brings us an endless list of knowledge sources. Many web sites provide useful information about vibration analysis. By using the related key words, i.e. vibration condition monitoring, spectrum analysis, machine failure diagnosis, and so forth, search engine will give a long list of URL (address) of those web sites. However, most of those web sites are commercial web sites that do business in on site vibration diagnosis service. Nevertheless, the screened web sites that provide very useful information are given below. Please be noted that the information is obtained in January 1999.

Julavisatkul [13] had used neural network in vibration analysis. He did experimentation on build up a model. He simulated the vibration signal from the model, a simple model. For example, he loose some bolt on the motor's frame to simulate soft foot. The result show that neural network can be used for problem analysis, but it need human experts to interpret the result. In addition, the simple model did not simulate noise level in real world operation, which, some places, high level of noise can intervene vibration analysis.

Chutima and Sagara [6] study about application of vibration condition monitoring of rolling bearing in maintenance planning. The research paper stresses on condition monitoring by employ the vibration analysis to lengthen the machine-

operating period. The level of severity and calculation of failure frequency is also presented.

http://www.cage.curtin.edu.au/mechanical/info/vibrations/tut1.htm

This web site provides many useful sources for student learning in the area of vibration analysis and Fast Fourier Transform. The tutorial section gives the basic knowledge of vibration analysis. Moreover, it gives the example of analysis of vibration data.

M file section present about the use of the Matlab file, the software that is used for calculation the mathematical equation, in vibration analysis. The testing method section presents the way to test the machine. The equipment for vibration analysis, i.e. accelerometers, is discussed. Furthermore, many useful links to related web site also be shown. Information that can be found are listed as hereunder.

- ✓ Tutorial
- ✓ Analysis of Example Vibration Data
- ✓ Testing Method
- ✓ M-Files
- ✓ Vibration Data Samples List
- ✓ Accelerometers
- ✓ Soundcard
- ✓ Links

http://www.vibetech.com/

This web site belong to Vibrant Technology. Its background is a California corporation founded in 1991. Vibrant Technology develops and markets software based systems for mechanical and civil engineering applications. The company principals have extensive experience in structural testing and analysis, multi-channel digital signal processing, parameter estimation, finite element analysis, and engineering software design. Many technical papers can be found in this web site.

In addition, Vibrant Technology is the developer of the ME'scope, a family of software products for analyzing noise and vibration problems in structures. The ME'scope is designed to aid the engineer working on: new product Research and Development, troubleshooting, manufacturing quality control, predictive maintenance, and monitoring of critical machines and structures. The ME'scope is available worldwide through a network of sales representatives or direct from Vibrant Technology.

http://www.vibinst.org/default.htm

This web site belongs to Vibration Institute. The institute is a not-for-profit organization dedicated to the exchange of practical vibration information on machines and structures. The scope of the Institute's activities also includes nonintrusive condition monitoring technologies. The institute establishes the Society for Machinery Failure Prevention Technology (MFPT). The Institute publishes Vibrations magazine,

Proceedings of its Annual Meetings, and Short Course Notes. Basic knowledge of vibration can be found in this web site.

http://inteltek.com/notes/rail2/index.htm

This is the official web site of Vast, Inc. They develop the diagnosis program called DREAM, Diagnostic Rolling Element Analysis Module, which has been introduced in many branches of industry and transport including railways

The useful sources in this web site are the developed diagnosis program. The following topics can be seen in the web sites.

1. Application of Bearing Diagnostics in Railway Repair Shops
2. Automatic System for Rolling Element Bearings Diagnostics

http://wisdom.arl.psu.edu/

This web site provides steps of predictive maintenance. Also do research in vibration diagnosis. The MURI – IPD, a multi-year grant to the Applied Research Laboratory (ARL) at the Penn State University, is employed in the research. Many tools and techniques are used in the MURI-IPD, such as Fast Fourier Transform, Fuzzy logic, Artificial Neural network, Statistic method, and so forth. The MURI-IPD is focusing on Condition Based Maintenance (CBM) for complex mechanical systems. The goal is to resolve issues allowing the diagnosis of the current state of a mechanical

system and to predict the remaining useful life. This research will lead to the development of Military and Commercial monitoring systems improved system reliability and human safety, platform life extension and reduced maintenance and lifecycle costs.

http://www.skfcm.com/newindex.htm

Actually, SKF, the bearing manufacturer, have many official web sites around the world. This web site belongs to SKF USA. Apart from detail of vibration instrumentation, the condition-monitoring concept, maximum service life of machine, is provide. Furthermore, techniques and cases used in spectrum analysis can be found in this web site.

http://www.cage.curtin.edu.au/mechanical/info/vibrations/intro.htm

The purpose of this web site is to assist student learning in the area of vibration analysis and the Fast Fourier Transform (FFT). It is also intended to provide information useful to engineers dealing with the problems of vibration measurement and analysis. The basic knowledge of vibration is provided on this site

- ✓ Tutorial
- ✓ Analysis of Example Vibration Data
- ✓ Testing Method

- ✓ M-Files
- ✓ Vibration Data Samples List
- ✓ Accelerometers
- ✓ Soundcard
- ✓ Links

http://www.brad.ac.uk/research/mbdmst/rotordynamic/links.html#Condmonnc

This is web site of university of Bradford in UK. This URL provide many of useful link in vibration field, such as condition monitoring, practical application, finite element model. The good point of this official web site is it classify non-commercial web link out of the commercial.

http://www.si-tes.com/

The web site of Southern instrumentation & technical equipment services provides the following service.

- ❖ Vibration Monitoring
- ❖ Condition Monitoring
- ❖ Basic Vibration Concepts
- ❖ Setup of PM Programs
- ❖ Monitor Calibration
- ❖ Ultrasonic Inspections
- ❖ Technical Training
- ❖ Onsite Oil Analysis

The basic vibration concept section gives a vital knowledge for vibration analysis. Consequently, the other techniques such as oil analysis and thermography technique are also provided on this web.

In addition, this is the example of commercial web site that provide both technical knowledge and commercial service.