Remote Machinery Condition Monitoring Using Wireless Technology and the Internet

by Lloyd Dewey Lee, Jr. "Buddy" of MAARS Inc.

Introduction

People have always desired to communicate with each other, and as communication technology advances, their desire to communicate grows with the possibilities offered by the technology. Modern technology enables mobile communications in many situations, including email, the Internet, wireless telephones and so on. The use of these technologies for Predictive Maintenance professionals can be critical to the success of the Predictive Maintenance program at an industrial plant.

With management trends such as "re-engineering" and "downsizing" of the available workforce, remote condition-monitoring of critical machines has been given more importance as a way to ensure quality production with fewer personnel. Remote condition-monitoring using inexpensive wireless communication technology frees up existing plant maintenance personnel to work on machines that are signaling problems, focusing the maintenance efforts away from attempting to work on a large population of machines to only those machines requiring immediate attention.

Point-to-point wireless data transmission systems, an excellent example of recent technological advances in communication systems, are now practical and cost-effective for industrial use. While both an infrastructure and a complex protocol are required for cellular communications, non-cellular communication systems, such as the point-to-point wireless data transmission system example, require no elaborate infrastructure. The systems considered here provide short distance (less than 20 miles), multi-access, ad-hoc based, point to point communication links.[1]

Figure 1: Wireless, point-to-point Communication System. This example shows the wireless Ethernet link between a monitoring system on an industrial machine transmitting vibration data to an end user's PC, where the vibration levels are displayed as gauges in real time.

A number of issues exist concerning a wireless communication system. Reasonable data-transmission speeds, reliability, security, ability to initiate a communication link at any time, duplex data transmission, a low bit error rate, short synchronization times, mobility, length of data transmission and an inexpensive infrastructure are just a few of the issues to consider. In addition to these, the issue of communication links that can be activated at any moment while several links are already simultaneously active is called "multiple random access".

Wired networks, on the other hand, are the backbone of the Internet and the World Wide Web. The Internet is a collection of thousands of networks linked by a common set of technical protocols which make it possible for users of any one of the networks to communicate with or use the services located on any of the other networks. These protocols are referred to as TCP/IP or the TCP/IP protocol suite. The World Wide Web is a distributed, hypermedia-based Internet information browser. It presents users with a friendly point and click interface via a web browser to a wide variety of types of information (text, graphics, sounds, movies, etc.) and Internet services.

Several sites on the Web are devoted to Predictive Maintenance and Machinery Reliability, from vendors of condition monitoring equipment to companies specializing in personal and web-based Predictive Maintenance training. For example, a search on Yahoo for the term “Predictive Maintenance” found 35 web sites and 31,599 web pages that have one or both words. The real value from using the World Wide Web is that instant information from these sites is made available at the time that the end user needs it. Just a few years ago, individual calls to each company would have been required to receive literature or information in which the user is interested. Now, in a matter of a few minutes time, all of the information can be downloaded for perusal at the end user’s leisure. In addition, the Web allows for communication in the form of message boards between users of particular technologies, such as vibration. Finally, with the development of advanced technologies for web content and presentation, such as Active Server Pages (ASP), it is now possible to query an individual network and have the network report significant information back to the user. As an example, vibration or process levels may now easily be transmitted over the Web and presented to the end user as gauges, reporting the condition of the remote machine in real time.

Classical maintenance programs at industrial plants have either let industrial machinery run until failure or implemented Preventative Maintenance. In the last 10 years, many plants have established Predictive Maintenance programs that utilize portable data collectors for data collection, storage, and analysis. This labor-intensive approach was acceptable until personnel began to be downsized. This downsizing, along with safety concerns, has resulted in accelerating the instrumentation (placing of sensors) on critical machines for process and vibration monitoring. Typically, a plant technician will run the cables connecting the sensors out to a termination panel, or box, where the end user will go to collect data with his hand-held meter. Unfortunately, the high cost of installing and maintaining the wiring and sensors for data collection is a major impediment to the widespread use of this method of data collection. Once installed, however, the usual next step is to connect all of these termination panels up to a computerized monitoring system. What is needed is a cost effective method of eliminating the wiring for these monitoring systems, and advances in wireless data transmission are quickly stepping up to the challenge. This paper presents the most promising technologies and an example of using these wireless systems for Predictive Maintenance.

Wireless Communication Technologies – Making the Case for Spread Spectrum

A commercial marketplace for secure digital communications is now emerging for commercial and industrial purposes. Applications for commercial and industrial communications include: wireless LAN's (computer to computer local area networks); integrated bar code scanner/palmtop computer/radio modem devices; digital cellular telephone communications; and city/area/state or country wide networks for passing faxes, computer data, email, or multimedia data. Applications for Predictive Maintenance include “Smart” sensors or machines that will automatically report when a degraded condition of the machine is detected.

Over the last 10 years, nearly every densely populated area of the United States has seen the proliferation of microwave towers erected by various commercial outfits. These towers are the backbone of the multi-access communication system infrastructure that we depend upon today for wireless communications. Several technologies are currently in use for multi-access communication systems, three of which we will introduce here:

1. **FDMA** (Frequency Division Multiple Access, commonly used in conventional telephone systems);

2. **TDMA** (Time Division Multiple Access, used in mobile phone systems but difficult to apply in random-access systems); and

3. **CDMA** (Code Division Multiple Access, also called Spread Spectrum).

CDMA, or Spread Spectrum communication techniques use wide band, noise-like signals that make them hard to detect, intercept or demodulate. In addition, Spread Spectrum signals are harder to jam (or interfere with) than narrow-band signals. The Low Probability of Intercept (LPI) and anti-jam (AJ) features is why the military originally developed Spread Spectrum techniques. Spread signals intentionally use a wider frequency band than the information they are carrying to make them more noise-like. Ironically, this feature makes these signals more immune to noise interference.

Figure 2: Graphic of Narrow Band vs. Spread Spectrum.

In Spread Spectrum systems, a unique code is assigned to each unit. This code is used to “code" the data message; therefore all units can transmit simultaneously in the same frequency channel while the receiver is capable of recovering the desired signal. Synchronization between links is not strictly required and so multiple random-access is possible between units on the wireless network.

There are a number of reasons for choosing CDMA over FDMA or TDMA. These include:

1. **Interference limited operation.** In all situations the whole frequency-spectrum is used.

2. **Privacy codes.** The applied codes are unknown to a hostile user. This means that it is possible, but very difficult, to detect the message of another user.

3. **Applying spread spectrum implies the reduction of multi-path effects.** By using a wide frequency-band, the influence of narrow-band fades is reduced.

4. **Random Access.** Users can start their transmission at any arbitrary time.

5. **Good anti-jamming performance.** Narrow frequency band interference is reduced.

Since Code Division Multiple Access enables multiple-access, it is the transmission technique used in spread spectrum systems. Spread Spectrum signals use fast codes that run many times the information bandwidth or data rate. These special "Spreading" codes are called "Pseudo Random" or "Pseudo Noise" codes because they are not real gaussian noise. In this technique, the frequency spectrum of a data-signal is "spread" using a code uncorrelated with the data-signal and unique to every addressee. Since every code is unique, it is possible to make a distinction between the different data-signals. Because the initiator knows the code of the intended addressee, the desired communication link is established.

The frequency bandwidth of the original data-signal increases when a data-signal is combined with a code. Therefore the spectrum is "spread" which is how the name "spread spectrum" was initiated. As the total transmitted power stays equal, the spectral power density decreases. The ratio of transmission and information bandwidth (called processing gain) is an important parameter in spread spectrum systems. The processing gain determines the total number of units in the system, the amount of multi-path effect reduction and the difficulty to jam or detect a signal. Therefore, it is a significant advantage to have a processing gain as high as possible for spread spectrum systems. [3]

Spread Spectrum transmitters radiate about the same power levels as narrow-band transmitters. However, since Spread Spectrum signals are so wide, they transmit at a much lower spectral power density, measured in Watts per Hertz, than narrow-band transmitters. The lower transmitted power density characteristic means that Spread and narrow band signals can occupy the same frequency band with little or no interference.

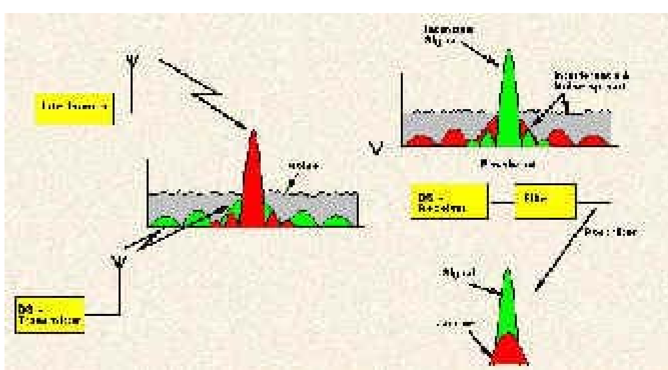

Figure 3: Spread Spectrum Signals reject interference very well. (Image courtesy of Jack Glas).[4]

Several different spread spectrum data transmission techniques exist. The two most popular techniques are Direct-Sequence Spread Spectrum (DSSS) and Frequency-Hopping Spread

Spectrum (FHSS). In addition, Time-Hopping (THSS) and Multi-Carrier CDMA (MC-CDMA), or a combination of these, may be used. For the purposes of this paper, only the DSSS and FHSS will be discussed.

Direct Sequence

Direct Sequence is the most popular Spread Spectrum Technique being applied today. The data signal is multiplied with a pseudo-random bit sequence often referred to as pseudo random noise code. Such bit-sequences have properties of spectral flatness and low cross and auto-correlation values (they are like noise in this respect), and therefore complicate jamming or detection by non-target receivers.

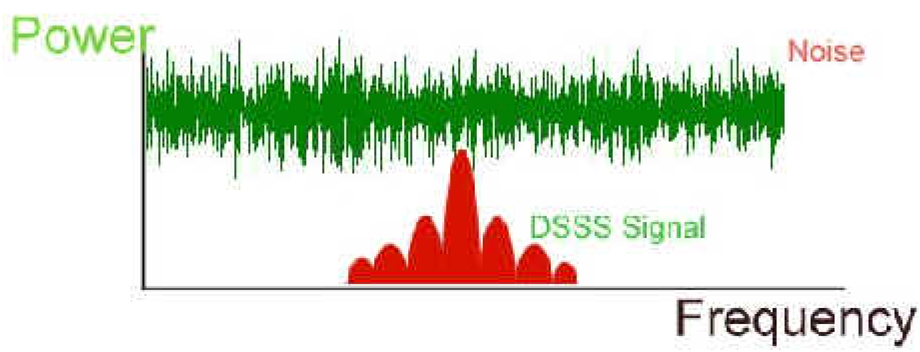

Figure 4: Direct Sequence Spread Spectrum Signal.

In direct-sequence systems the length of the pseudo-random code is equal to the spreading-factor. The power content, however, stays the same, with the result that the spectral power density is lowered. Because the generation of pseudo-random codes is relatively easy, the ability to obtain a large processing-gain in Direct-Sequence Spread Spectrum systems makes them popular in use for commercial systems.

At the receiver, the signal is multiplied again with the synchronized pseudo-random code. This de-spread procedure completely removes the code from the signal and the original data-signal is recovered. Because the de-spread procedure is the same as the spreading procedure, jamming effects are reduced because a possible jamming or interference signal in the channel will be spread before data-detection is performed.

A large problem with multi-access direct sequence spreading is the near-far effect. This effect is present when a CDMA interfering transmitter is much closer to the receiver than the intended transmitter. Although the cross-correlation is low, the correlation of the received signal from the interfering transmitter in the receiver can exceed the correlation of the received signal from the intended transmitter and the correct code. For example, a typical commercial Direct Sequence Spread Spectrum system might have a processing gain of from 11 to 16 dB, depending on the data rate. This system might tolerate total jamming signal power level range from 0 to 5 dB stronger than the desired signal, but performance of the DSSS system will become degraded in this scenario.

Frequency Hopping

The other most popular technique for Spread Spectrum data transmission is Frequency Hopping (FHSS). In frequency hopping, the carrier frequency shifts or "hops" according to a unique sequence. In this technique, the number of discrete frequencies determines the bandwidth of the system. Therefore the process gain is directly dependent on the number of available frequency channels for a given information rate. In this way the bandwidth is increased if the channels are non-overlapping. FHSS is less vulnerable to the near-far effect than direct-sequence, because FHSS sequences have only a limited number of "hits" with each other. This means that if interference from a nearby unit or another signal source is present, the whole signal is not blocked, but only a limited number of frequency-hops. From the "hops" that are not blocked it is possible to recover the original data-message by applying error correction techniques.

An important factor in FHSS systems is the rate at which the hops occur. The information bit rate, the amount of redundancy used, and the distance to the nearest interference source determine the minimum time required to change the frequencies.

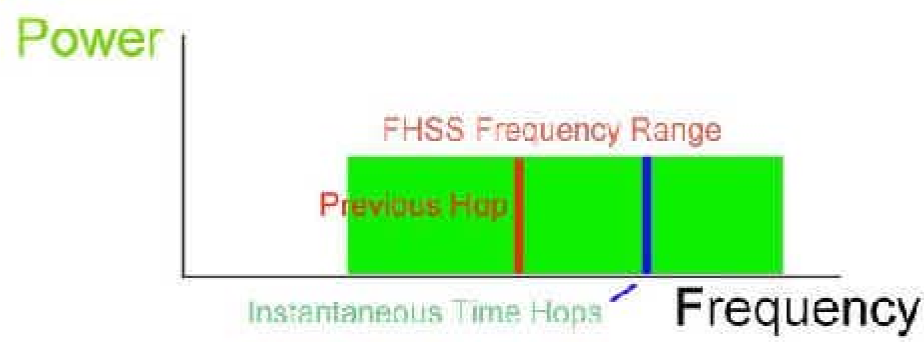

Figure 5: Frequency Hopping Spread Spectrum.

The FHSS transmitter is a pseudo-noise (PN) code-controlled frequency synthesizer. The instantaneous frequency output of the transmitter jumps from one value to another based on the pseudo-random input from the code generator. Varying the instantaneous frequency results in an output spectrum that is effectively spread over the range of frequencies generated. A synchronized pseudo noise code generator that drives the receiver's local oscillator frequency synthesizer performs de-hopping in the receiver.

A disadvantage of frequency hopping compared to direct-sequence is that it is harder to obtain a high processing gain for frequency hopping systems. A frequency synthesizer is required that is capable of rapidly hopping over a set of carrier frequencies. With more carrier frequencies, the processing gain is increased, but the demands on the frequency synthesizer increase significantly.

Now that we have discussed multi-access communication systems and the implementation of the most popular types of Spread Spectrum technologies, namely FHSS and DSSS, we will examine the roles of the FCC and the IEEE in the wireless arena.

The Federal Communications Commission and Spread Spectrum

The FCC establishes licensing and other legal requirements for operating any radio transmitter. These change from time to time, and the reader should consult the FCC Regulations for the latest information.

The Federal Communication Commission's (FCC) position on unlicensed operation is found in Part 15 of the FCC Regulations. Part 15 mandates unlicensed equipment must (1) not cause harmful interference, and (2) accept any harmful interference to its own operation. The FCC strictly limits power from devices regulated under Part 15 to achieve these goals.

The FCC favorably treats spread spectrum usage, based on several technical points. Since spread spectrum was designed to be difficult to intentionally intercept, it is also difficult to unintentionally intercept or receive. Therefore, it presents less of a threat of harmful interference than non-spread spectrum devices. As a result, the FCC allows spread spectrum devices up to one watt of transmitter power.

Most non-Spread Spectrum Part 15 unlicensed systems can operate over a 300 foot outdoor range. By comparison, a spread spectrum transmitter operating at only ten percent of the maximum power permitted by the FCC (that is, 0.1 watt), has a ground level outdoor range of one to one-and-a-half miles. If one antenna is elevated to 200 feet, that range may extend to 17 miles.

The FCC permits unlicensed operation in portions of the spectrum called ISM (Industrial, Scientific and Medical) Bands provided that certain technical restrictions on transmitter power and modulation are met. The provision of the license-free ISM bands has boosted a lot of other terrestrial wireless applications. Well-known ISM bands are the 902-928 MHz band in the US, and the 2.4-2.4835 GHz band worldwide. Designated frequency bands vary with the specific device and the application. Below is a general run-down of several major frequency bands, along with some common devices operating in them.[5]

Part 15 devices use the 900 MHz, 2.4 GHz and 5.7 GHz frequency bands. Typical handheld radios and other devices usually present in industrial settings are in much lower frequency ranges, and so offer little chance of interference with Part 15 Spread Spectrum devices.[6]

The Major Wireless Standards

Several major wireless communication standards exist today. Below is a short list of the major standards:

1. **IEEE** - 802.11 is the IEEE standard for wireless LAN's. The goal of the IEEE 802.11 committee is to standardize wireless LAN development in the ISM Band.

2. **IrDA** - The Infrared Data Association (IrDA) was formed to develop a standard for wireless communication using infrared (IR) technology.

3. **AMPS** - Advanced Mobile Phone System. AMPS is the first analog cellular standard in the U.S. Although AMPS is still in use, it is anticipated that it will be replaced by the United States Digital Cellular(USDC) standard.

4. **GSM** - Global System for Mobile. The GSM standard was developed in Europe to standardize cellular communications in Europe. GSM is now one of the world's most popular standards for new cellular radio and personal communications equipment.

5. **USDC** - United States Digital Cellular, also known as IS-54 (Interim Standard 54), was developed to replace the AMPS standard, particularly in urban areas where AMPS did not provide adequate channel capacity.

Of these standards, the IEEE 802.11 is the most popular for data transmission in an industrial environment in the U.S. It is the first standard for WLAN systems from an internationally recognized and independent organization. In 1990, the IEEE 802 standards committee formed the 802.11 Wireless Local Area Networks Standards Working Group. The 802.11 working group recently completed the global standard for equipment and networks operating in the 2.4GHz unlicensed ISM frequency band. The membership of the committee consists of manufacturers of semiconductors, computers, radio equipment, WLAN systems solution providers, University research labs and end-users.

The 802.11standard permits manufacturers of wireless LAN radio equipment to build compatible network equipment by defining the protocol for ad-hoc and client/server networks. An ad-hoc network is a simple network where communications are established between multiple stations in a given coverage area without the use of an access point or server. The etiquette that each station must observe is defined with methods for arbitrating requests to use the media to ensure that throughput is maximized. Client/server networks use an access point that controls the allocation of transmit time for all stations and allows mobile stations to roam from cell to cell, handling traffic from the mobile radio to the wired or wireless backbone of the client/server network.

Modulation and signaling characteristics for the transmission of data are defined at the Physical Layer in any network. In most countries, operation of the WLAN in unlicensed RF bands requires the use of spread spectrum modulation. The wireless transmission standards in the 802.11 standard are Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS). Both methods are defined for operation in the 2.4GHz frequency band occupying 83 MHz of bandwidth from 2.400 GHz to 2.483 GHz. The choice between FHSS and DSSS will depend on the application and the environment in which the system will be operating.

The IEEE 802.11 WLAN standard will be one of the first generations of standardization for wireless LAN networks. This standard will set the pace for the next generation standard, addressing the demands for increased performance using faster data rates and higher frequency bands. Compatibility between WLAN products from different manufacturers is critical to the success of the standard, and these products will be implemented on ISA or PCMCIA hardware for use in handheld computers, laptops or desktop applications. Over time, the increase in demand for 802.11 systems should increase competition and make wireless LANs more economical for all applications requiring wireless communications. [7]

Using the Internet for Condition Monitoring of Machinery

As stated in the introduction, the Internet is a collection of thousands of networks linked by a common set of technical protocols which make it possible for users of any one of the networks to communicate with or use the services located on any of the other networks. The World Wide Web is a distributed, hypermedia-based Internet information browser. It presents users with a friendly point and click interface to a wide variety of types of information (text, graphics, sounds, movies, etc.) and Internet services such as Predictive Maintenance and Machinery Reliability websites.

One of the most popular message boards on the web for Predictive Maintenance discussions is at the Reliability Magazine website. Users typically post questions relative to vibration diagnostics, for example, and receive information from other users of the message board. The message board may be accessed at www.reliability-magazine.com. Another site that is gaining popularity is www.reliabilityweb.com. Of course, many sites exist that are commercial sites for Predictive Maintenance system and service providers. Searches can be performed for terms such as "Predictive Maintenance", "Vibration Analysis", and so on. A couple of related sites that may be of interest include www.sensorsmag.com, the website of Sensors Magazine, and www.manufacturing.net/magazine/planteng the website of Plant Engineering Magazine. In a timely coincidence, the June 2000 Edition of Plant Engineering Magazine online ran an article titled "The Internet and the Plant Engineer" by Jeanine Katzel, Senior Editor, with the results of an informal survey:

"The top three reasons our respondents said they surf the net are to learn about and compare products, to locate vendors, and for news and information. More than half those answering this question ranked these activities first, second, or third. Obtaining technical help and seeking parts information are two other popular reasons respondents gave for turning to the internet.

And what benefits does searching the internet bring? Nearly a third of those responding to the survey said the web increases job efficiency. Another third said it increases available options and product choices. More than a quarter said it saves time." [8]

Certainly the use of the internet is still in its infancy, and with the development of advanced technologies for web content and presentation, such as Active Server Pages (ASP), it is now possible to query an individual network and have the network report significant information back to the user. As an example, vibration or process levels may now easily be transmitted over the Web and presented to the end user as gauges, reporting the condition of the remote machine in real time.

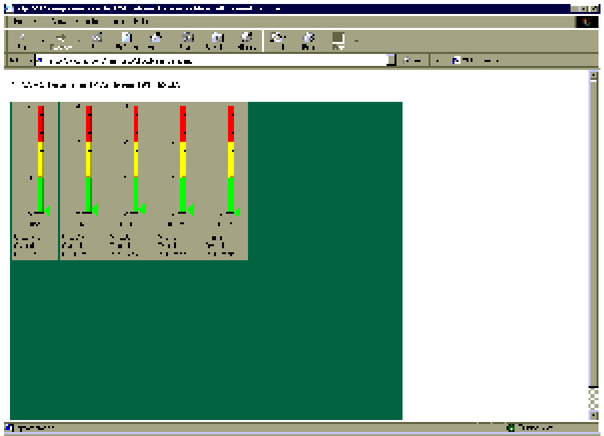

Figure 7: Internet browser showing vibration gauges.

Use of the internet for remote machinery monitoring in addition to e-commerce and information gathering will certainly continue to grow in popularity, especially as the wireless internet and technological advances of internet technology, such as Internet2, continue to progress.

A Peek into the Future…

A new version of the Internet called Internet2 that is in use by academia, scientists and engineers, has much promise for fast data transmission.

Internet2 – The Sequel

Internet2® is a not-for-profit consortium, led by over 170 US universities. Internet2 is not a separate physical network and will not replace the Internet. With participation by some 60 leading companies, Internet2 recreates the partnership of academia, industry and government that helped foster today's Internet. The legacy of Internet2 will be to expand the possibilities of the broader Internet.

A key goal of this effort is to accelerate the proliferation of advanced Internet technology, in particular into the commercial sector. In this way, Internet2 will help to sustain United States leadership in internetworking technology. All the buzz about Internet 2 (the bigger, better, stronger brother of the current Internet) makes it hard to figure out just what I2 is, let alone what it does or can do.

The main advantages of I2 are speed and reliability, because it has safeguards to make sure data packets are delivered. I2 is capable of higher bandwidth, multicasting, guaranteed delivery and performance. Note that a standard 10Base T Ethernet card transfers data at 10 megabits per second, and 100Base T Ethernet cards transfer data at 100 megabits per second. Internet 2 Ethernet card transfer rates are in the gigabits. For example, a team from the University of Washington, the Information Sciences Institute of the University of Southern California, Qwest and Microsoft set a new standard for Internet performance by transferring 8.4 GB worth of data from Redmond, Washington to Arlington, Virginia (5,626 Km) in 81 seconds at a rate of over 830 megabits per second!

Commercial development of I2 will be going on simultaneously to the academic one. The commercial transition will happen very quickly because companies like AT&T, Sprint, and MCI have been watching the progress closely. And, because I2 is designed to take advantage of existing "off-the-shelf" technology, switch and router makers, like Cisco Systems, will continue to push the capabilities of their products and make them available to the private sector. Applications for Predictive Maintenance that could be developed from this technology are in the areas of vibration sensor wire replacement and termination box replacement. In addition, since the power requirements are so low, this technology may help make battery powered vibration sensors viable (this has been the main drawback to making the sensors wireless, as vibration sensors require a power supply to work).

Having now discussed the important technologies and standards that enable wireless systems development, we will turn our attention to using these technologies and standards in the application to plant machinery condition monitoring.

Machinery Dynamics and Data Fusion via Remote Condition Monitoring

Most industrial plants today have a good “handle” on the electrical and chemical processes in the plant. The Process Engineering division monitors and controls these two “rivers” of information, which produce important information about the plant’s capacity to make quality product(s). An essential third river of information is the health, or condition of the machine. Typically, this river of information is not being monitored in real time, and it is often left to the maintenance department to determine the machine’s health on a monthly or even quarterly basis through specialized vibration testing.

By knowing the condition of the machine from a mechanical vibration standpoint and correlating the vibration information with the process (temperature, pressure, flow, strain, etc.) information, maintenance personnel will able to determine the likelihood of the machine producing quality parts (or even just operating) into the future. In addition, by tracking the cost per hour of operating the machine in real time, machine operators control over the machine to operate it in the most efficient manner possible while at the same time making the highest quality product possible. Significant savings to the plant’s bottom line could be realized by monitoring the machinery’s condition in real time (which we term “Machinery Dynamics”).

"Machinery Dynamics" is a new philosophy of Plant Engineering that will encompass both the Process Engineering and Plant Engineering (Maintenance) side of an industrial facility. Machinery Dynamics is defined as the application of Statistical Process Control techniques and methodology (process control) to the machinery diagnostics side (Maintenance). Some would argue that plants are already performing both of these functions, however, in the real world, neither Maintenance nor Process Engineering does an adequate job of communicating with each other. The result is a "tug-of-war" between maintenance and production over running the machine or performing maintenance.

What is needed is a new philosophical and technical methodology of performing machinery diagnostics on the machine(s) to make the dream of machinery reliability a reality for thousands of plants. This will be accomplished by manufacturing a "dual mode" monitoring unit capable of monitoring channels (sensors) all the time (continuously) for critical machines, and selected sensors for support equipment (necessary, but not critical machines) on a time basis. To make this system practical for implementation, wireless data transmission is required. By enabling the system to have inputs from any kind of sensor (vibration, temperature, pressure, flow, strain, tachometer, eddy current, amperage, voltage, etc.), the machinery vibration (behavior of movement) may be correlated with the process information (ergo "Data Fusion"). By digesting this data through a learning machinery diagnostics software package, as failures are recorded the end user would be able to produce "Machinery Failure Models". These models will give the operator(s) advance warning before failure the next time that the machine violates a design or operational curve parameter.

This system would allow the end user to custom configure his monitoring system to his particular machinery, providing him with an "Application Specific Solution." The Failure Models generated are therefore customized to his plant, and although in the beginning it makes sense to have generic models available, very quickly the customer can manipulate the system to fit his equipment. This should also increase the accuracy of calls on degraded equipment, since each time a failure occurs, the system will learn to avoid or alarm when the condition is seen again. The application of Statistical Process Control methods to the fused data from the system will enable the system to have high reliability of diagnostic recommendations. Perhaps the best advantage of Machinery Dynamics is that the concept will give both Maintenance and Operations the tool to gain management support for the most efficient operation of the machinery.

Systems that will enable Machinery Dynamics are currently being developed by a host of companies, including sensor manufacturers, the government research labs, wireless data transmission and condition monitoring system companies. The first step to implementing wireless technologies with condition monitoring systems is to replace the wired Ethernet connection from a termination box to the plant network. In the example application below, a system doing exactly this has been operational for over a year. Within the next year or so, the wire between the sensor and the termination box will be replaced with wireless data transmission, providing that the sensor power issue can be be resolved.

Using Wireless Ethernet Example Application

This example illustrates the use of an online monitoring system for vibration analysis of an Overhead Crane in an industrial application. The application is implemented at an aluminum roll manufacturing facility on the Continuous Cold Mill Exit Crane. This crane must handle every pound of aluminum that is produced by the facility, so it is critical to the roll production process.

A preventative maintenance program was established for the crane, but failures of the crane components were still of concern. The crane is inspected manually by the operator on a time basis, and yearly by a contract crane rebuild shop. Safety concerns preclude the use of a portable data collector to acquire vibration data from the crane while it is running. An online monitoring system was permanently affixed to the crane in April of 1999. Sensors are hardwired along the festoon from the crane components to the monitoring system. Wireless spread-spectrum data transmission is used to send the vibration data down from the crane to the plant Ethernet network, where the data can be accessed by any computer on the company network.

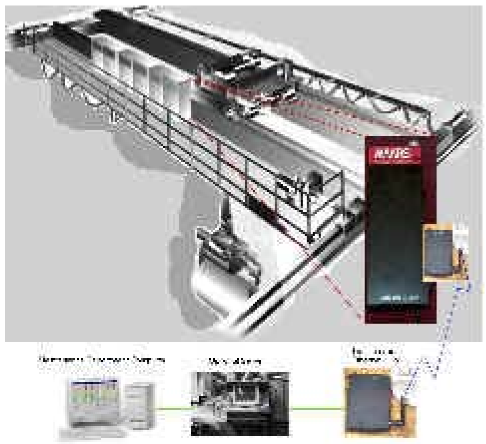

Figure 9. Wireless Monitoring System for Overhead Crane.

System Architecture

The crane monitoring system consists of two main components – 1) the crane monitoring unit located on the crane, and 2) a optional PC-based server which can be located anywhere on the network. These two components are described in more detail below.

A wireless spread-spectrum transceiver is connected to the side of the monitoring unit that transmits the data from the crane via Ethernet to the server, where another transceiver receives the data.

The specific architecture of the system used for the included case history is as follows:

1. Six vibration sensors are connected to the system, four on the hoist gearbox and two on the DC drive motor.

2. One passive magnetic tachometer is mounted on the 8-foot shaft connecting the motor to the gearbox.

3. The sensors are hard-wired to the crane monitoring unit by running the sensor cables along the crane festoon.

4. No load detection sensors, such as strain gauges or current sensors were required on the system because the crane has approximately the same load on each lift and lower cycle. For cranes that have variable loads, such inputs would be desirable for vibration trending of similar loads on the crane.

Application of Vibration Technology

Vibration analysis of production cranes has proved to be very successful in reducing the number of unplanned crane outages at the aluminum production facility. Classical predictive maintenance programs trend data from a large population of machines, looking for imbalance, misalignment, looseness, shaft, bearing and gear defects, foundation problems and electrical defects in motors. These problems may now be identified and corrected before catastrophic failure on overhead cranes using the crane monitoring system.

Critical to the detection of these problems is the employment of vibration frequency bands, commonly called analysis parameters. Trends of these parameters often signal degraded machine condition. Several analysis parameters were defined to aid in diagnosis of internal problems in the hoist drive and gearbox. Alarm limits were assigned to the parameters to provide predictive and diagnostic capability. A special data collection technique, called order tracking, is used to avoid smearing of the data in the display of the FFT. This technique accounts for these small speed variations during data acquisition.

In addition to the techniques presented above, the following information is critical to the complete monitoring of the crane:

1. The DC motor has an SCR firing frequency of 360 hz, and we will want to take this into account in addition to the bearing and gearmesh frequencies introduced below.

2. The gearbox is a triple-reduction, with three gearmesh frequencies calculated from the following table for typical RPM values.

Input RPM	GM 1	GB Shaft 1 RPM	GM 2	GB Shaft 2 RPM	GM 3	Drum RPM
600	10200	115	1719	32	454	11
610	10370	117	1748	33	462	12
620	10540	118	1776	34	469	12
630	10710	120	1805	34	477	12
640	10880	122	1834	35	484	12

Table 2. Gearmesh Frequencies for the Crane

In vibration analysis, often we are presented with harmonics of the gearmesh frequencies of 2X or 3X the fundamental gearmesh. The following table shows the 2 and 3 X gearmesh harmonics:

GM 1	GM1 - 2X	GM1 - 3X	GM 2	GM 2 - 2X	GM 2 - 3X	GM 3	GM 3 - 2X	GM 3 - 3X
10200	20400	30600	1719	3438	5157	454	908	1362
10370	20740	31110	1748	3496	5244	462	924	1386
10540	21080	31620	1776	3552	5328	469	938	1407
10710	21420	32130	1805	3610	5415	477	954	1431
10880	21760	32640	1834	3668	5502	484	968	1452

Table 3. Gearmesh Frequencies and Harmonics for the Crane.

In addition to knowing our gearmesh and internal shaft frequencies, it is also important to know the bearing frequencies that are present in the machine. Bearing manufacturers freely give out their bearing fault frequencies, which consist of the fundamental train frequency; the ball spin frequency; the outer race ball pass frequency and the inner race ball pass frequency. Note that the actual location of these frequencies is dependent upon the turning speed of the shaft which each bearing supports. In addition to the fundamental frequencies, harmonics of these frequencies may also be present.

Beginning with the gearbox input shaft, we see from the following table that the bearing frequencies and harmonics for the input shaft bearing (SKF 22217) are:

Harmonic	Speed	BPFI	BPFO	FTF	BSF
1	600	6124	4,676	260	2,163
2	1200	12,248	9,352	520	4,326
3	1800	18,373	14,027	779	6,489
4	2400	24,497	18,703	1039	8,652
5	3000	30,621	23,379	1299	10,815
6	3600	36,745	28,055	1559	12,978
7	4200	42,869	32,731	1819	15,141
8	4800	48,994	37,406	2078	17304
9	5400	55,118	42,082	2338	19,467
10	6000	61,242	46,758	2598	21,630

Table 4. Bearing Frequencies for the Gearbox Input Shaft.
Frequencies calculated in CPM Brg Mfg: skf Brg Num: 22217 RPM: 600

Note that here we have only calculated the bearing frequencies for the lowest RPM. We can also perform this process for the other gearbox shafts, but in the interest of brevity, we will not show these tables in this paper. The other bearings found in the gearbox are an SKF 22218 on the first internal shaft, an SKF 22224 on the second internal shaft, and an SKF 22220 on the output shaft turning the drum.

Now that we have a fundamental understanding of the frequencies that are present in the crane motor and gearbox components, we can turn our attention to actual data collected on the crane and begin looking for frequencies generated by these components.

For our first example, we will look at what we believe to be a developing bearing problem on the gearbox input shaft. Note from the data table above for the input shaft bearing that the calculation on the BPFO for a 600 RPM input speed is 4,676 CPM. Checking our spectral information, we found this frequency (or very close to it - 4,582) and some harmonics of this frequency that help us understand the peaks seen in the spectral data. As you can see from the following images, the RPM on the shaft varied between 610 and 640 RPM.

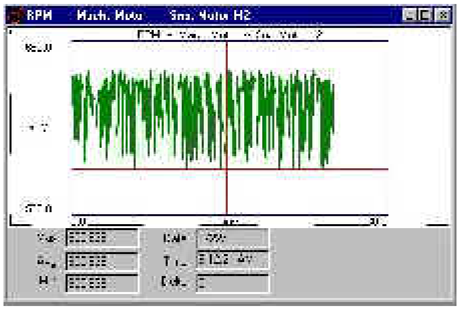

Figure 10. RPM Variations on the Crane.

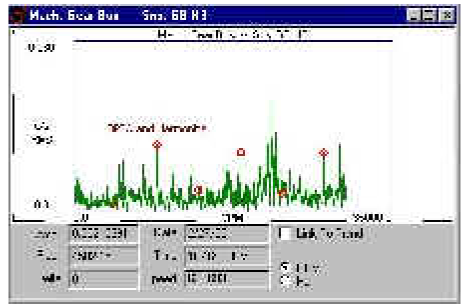

Figure 11. BPFO and Harmonics.

The above spectrum indicates that the BPFO frequency at 4582 CPM has higher harmonics at 2X, 4X and 6X the BPFO. This data was acquired on the sensor that is closest to the input shaft, however it is in a horizontal position. Often bearing frequencies may be more prevalent in the axial direction on a gearbox. The closest sensor that is in the axial direction is the A5 sensor, shown below, which also has these frequencies presented in the spectral display. Analysis of the other peaks in the spectrum did not indicate any harmonics of the other fundamental bearing frequencies.

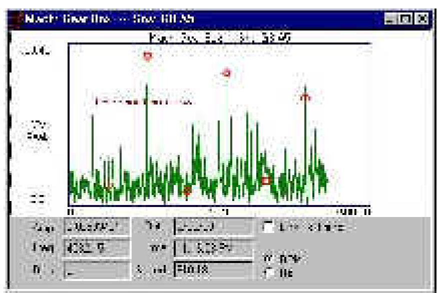

Figure 12. BPFO on the Axial Sensor.

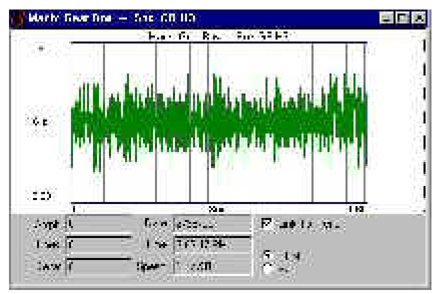

Figure 13. Time Waveform with Impacting.

Impacting in the time waveform is often used to confirm the spectral data for bearing problems. Note from the waveform data presented here that impacting is beginning to modulate the waveform data, a **classic** indication of a developing bearing defect.

For our second example, gear defects in the crane hoist gearbox proved one of the most easily identifiable defects. One can see from the data shown that this defect is easily identifiable through spectral analysis.

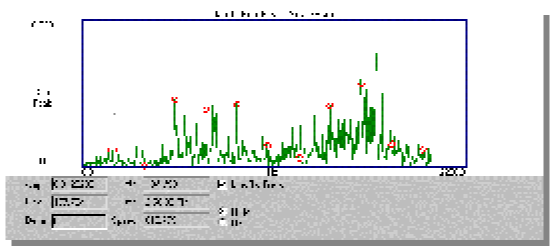

Figure 14. Spectrum of Gear Defect.

In this spectral data collected last October, the peaks dominating the spectrum are harmonics of the gearmesh of the input shaft. Here we show the main GM frequency as 177 hz, which is

10,640 CPM. This value falls right in line with the values given for the GM frequencies in the previous table. Note particularly how high the 3, 4, and 5 times gearmesh harmonics are relative to the other peaks in the spectrum.

Running through the data to inspect for bearing frequencies did not result in any ascertainable results to pinpoint bearings as a problem, and the frequencies indicated with the harmonic cursors shown above corresponded to the GM frequency of the input shaft.

Conclusion

Recent advances in sensor technology, along with computational power and wireless communications, have enabled machines that were once thought to be difficult to monitor to be added to the list of machines that can be effectively and inexpensively monitored. This paper explored the technological developments of Spread Spectrum wireless systems and the Internet and the application of these technologies to Predictive Maintenance. In addition, future developments of wireless systems and the application of these systems to Machinery Dynamics were presented. The Case History explored the use of an online monitoring methodology that met or exceeded these challenges, and then presented two examples that showcased the practical application of vibration analysis as a fundamental component of this methodology.

References

1. Weisman, Carl *"The Essential Guide to RF and Wireless"* Prentice Hall, NJ, 2000.

2. Roberts, Randy *"Spread Spectrum Primer"* Virginia Polytechnic Institute, www.SSS-mag.com, 1998.

3. Glas, Jack *"The Principles of Spread Spectrum Communication"* Delft University, Circuits and Systems Group, http://cas.et.tudelft.nl/, the Netherlands, 1998.

4. www.fcc.gov

5. Center for Wireless Telecommunications, www.cwt.vt.edu FAQ,Virginia Tech, Blacksburg, VA 1999

6. WLANA Commentary, The Wireless LAN Association, www.wlana.com

7. Katzel, Jean *"The Internet and the Plant Engineer"*, Plant Engineering Magazine, June 2000

8. Lee, Buddy *"Machinery Dynamics",* MAARS Business Plan, MAARS, Inc. 1996.

9. Lee, Buddy *"Crane Monitoring Application Note",* MAARS Application Paper, MAARS, Inc. 1999.