Condition Based Monitoring of Converting Line Equipment

Josefin Brodelius and Madeleine Rosengren

November 23, 2010

Abstract

Condition Based Monitoring techniques have been developed to monitor the condition of critical components in machines. The most widely used technique to detect damage in machine components is vibration monitoring, but there are areas where other methods could be a better option. Vibration measuring can also be used as a broader search for damage in components while other methods can specify the exact location and type of damage. Other CBM methods can be oil analysis, thermography, ultrasonics, Motor Current Signature Analysis, electrical testing and Coast Down Time.

The purpose of this master thesis is to define critical components in Tetra Pak converting machines, investigate possibilities of applying CBM techniques and to recommend and set up solutions for both converting lines.

To gather and analyze break down statistics, in the hope of identifying critical components, the software QlikView was used. Unfortunately, this did not give a better idea of the problem areas and another approach had to be taken; critical components were identified based on the cost for obtaining new parts and the lead time for them to be delivered. In this way two critical areas were identified; the drives in the extruder and printing stations.

The decision was to online monitor these drives with vibration measurements and different companies with online vibration monitoring systems were consulted. What company to use is difficult to say before executing test installations of the systems and analyses of the results, but all companies were willing to provide this service.

Placement of transducers on the components has been suggested. Variable rotational speeds, various diameters of cliché rolls and different print patterns in the printing stations can become a problem when teaching the system "normal vibrations", but this can be solved by triggering the system to only measure during specific conditions and process parameters. Another problem can be the large thrust bearing in the extruder station, which rotates with low rotational speed. This can probably be solved by using special shock pulse techniques for measuring at low rotational speeds or oil analysis on the return oil from the thrust bearing.
Keywords: Condition based monitoring, Vibration, FFT, Bearings

Preface

This is a Master Thesis made at Tetra Pak with support from the division of Machine Elements at Lund University in the fall 2010.

We would like to thank our supervisor at Tetra Pak Johan Brunlid for his support during our work and also thank you to Johann Steiner, Peter Larsson and Mats Göransson for their support and ideas of where to focus and make progress with our research.

A great thank you to Bengt Olsson at Tetra Pak who shared his knowledge of vibration measuring with us and answered many of our questions. When he did not know the answer he helped us find out in other ways.

We thank our supervisor at Lund University Lars Vedmar for his support and expertice.

Lund 2010-11-23

Josefin Brodelius and Madeleine Rosengren

Contents

Chapter 1

Introduction

1.1 The company

In 1951 Ruben Rausing and Erik Wallenberg started Tetra Pak in Lund, it was a subsidiary of the company "Åkerlund och Rausing" , that was founded in 1929 with the purpose of making cartons for pre-packaged foods. The vision was to with a minimum of material and maximum hygiene create a package for milk.

Today Tetra Pak provides packaging and processing systems, incorporating processing equipment, packaging machines, distribution equipment and complementary software services. Tetra Pak packages are available in more than 170 countries [1].

In this master thesis the focus is on the printing machine VT Flex 175 ES and the laminator VT Lam 650/6 WRM. These machines are part of converting paper into packaging material. A description of the machines will be given in appendix B.

1.2 Problem description

Today most of Tetra Pak's converting machines run without being continuously monitored. The cost if a break down occurs could possibly be very large since the machine might have to stand still for many hours or days. With the possibility to monitor the machine during production comes the possibility to discover approaching break downs and large cost could be avoided.

The goal with this master thesis is to investigate the possibility to introduce continuous monitoring in the printing machine VT Flex 175 ES and the laminator VT Lam 650/6 WRM.

When monitoring the condition in a machine it is possible to detect future failures at a very early date which enables planned maintenance and prevents unexpected break downs. Since the machines are quite large, approximately 30 meters long and 4 meters wide, it would be very expensive to monitor the whole machine. Therefore the sections and components of the machines that are possible and essential to monitor should be identified.

To identify possible monitoring techniques a broad study of what is possible to monitor will be performed. Critical components will be identified and after that studies of what techniques to use and how to apply the different techniques onto the critical components will be performed.

1.3 Delimitations

This thesis is limited to study the possibility to introduce Condition Based Monitoring in printing machine VT Flex 175 ES and the laminator VT Lam 650/6 WRM. The monitoring techniques are, however, applicable to any other of Tetra Pak's converting machines.

No tests of different CBM systems will be performed during the work with this thesis and the results will therefore solely be derived from a theoretical basis. Meetings with suppliers and studying of product data sheets will be performed as a complement.

The laminator in the factory in Lund is not a proper VT Lam 650/6 WRM, it is an older machine that is rebuilt to function like the new VT Lam 650/6 WRM. The function of the machines are basically the same but the gearboxes, motors or other components might be different and before installing a CBM system on a VT Lam 650/6 WRM that type of machine needs to be analyzed more deeply.

1.4 Expected results

The purpose of this project is to:

- Investigate and present different CBM methods
- Find problem areas in the machines where CBM can be used to prevent break downs and save money
- To recommend and set up solutions for both Converting Lines including interface towards and visualization in Human Machine Interface (HMI)

Chapter 2

Method

2.1 General method

The approach used in this project is based on the model for Creative Problem Solving (CPS). CPS was developed in the 1950s by Alex Osborn and Dr. Sidney J. Parnes and has been used since then to generate solutions to problems in a structured way. The process consists of three steps that each starts with a broad search for many solutions and alternatives and after that, evaluation and selection of the best solution[22]. Some interpretations and modifications are made to better fit this project. The steps with some explanations are presented below.

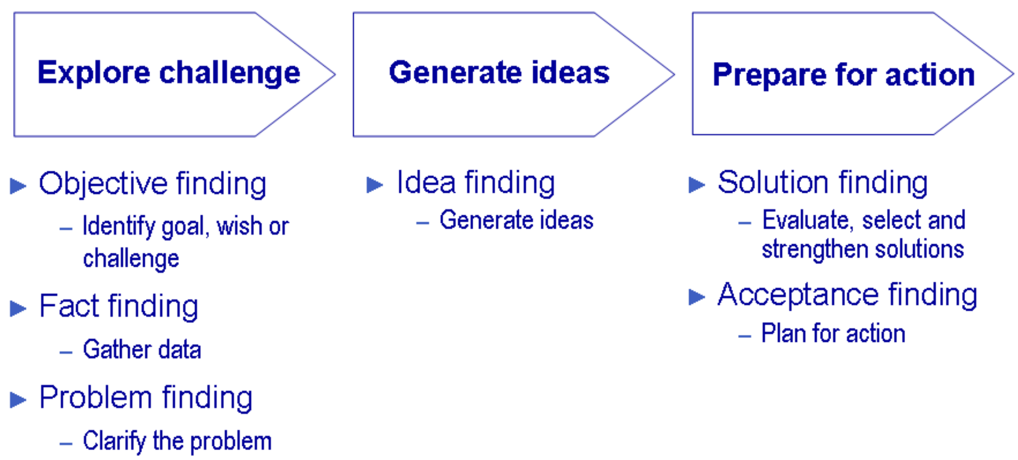

Figure 2.1: Method

During the first part of the project there will be a general search of information within the field of Condition Based Monitoring. The search will then be narrowed and concentrated to applications and existing systems on the market. A benchmarking will also be performed to identify what types of systems exist on the market. The problem finding stage of the project is where statistics will be analyzed to clarify where the biggest problems are and where to concentrate the resources.

An email survey will be done at Tetra Pak's factories to gather information on what is done in the factories today within condition based monitoring. The result of this survey is presented in appendix C.

After identifying systems on the market economical aspects will be considered as well as functional. In the last part of the project the different CBM systems will be evaluated and a recommendation of what systems to apply will be made.

2.2 Literature

The first part of the project is an extensive study of literature. The search for information will mainly be performed on the internet in various data bases such as ELIN (Electronic Library Information Network) which contains a vast amount of articles, e-books and magazines. The market of existing products will be examined by researching the information handed out by suppliers on their web pages, in their product data sheets and by performing interviews.

When conducting a literature study it is important to only use information from reliable sources such as books and articles written by trustworthy authors or companies. During the studying of information handed out by suppliers of CBM systems it is vital to remember that they want to sell their product and are unlikely to present possible downsides with their product.

2.3 Qualitative vs. quantitative information

Quantitative research is when a large amount of information is gathered, sorted and analyzed, qualitative research on the other hand focuses on a small amount of information that is analyzed deeply [14, p. 30].

In the research part of the project the main focus is on retrieving information about Condition Based Monitoring, its applications and companies supplying systems for CBM. This part will be a qualitative information gathering where the focus is on the information itself instead of the amount of information.

In the later parts of the research a quantitative search will be done when the collecting of statistics begin. This collection of statistics will be done both in a program called QlikView, that will be presented in chapter 4, and by contacting Tetra Pak factories all over the world and collecting the information directly from them.

2.4 Interviews

During the search for information a series of interviews will be performed. The interviews will be unstructured which means that they are not following a strict list of questions but instead they will take the form of a conversation. During the interview the respondent is given the possibility to explain their view of things and bring up subjects he or she finds relevant [12, p. 69].

Chapter 3

Theory

3.1 CBM

A significant part of the total costs for producing a product is the costs for maintenance, in the paper industry and other heavy industries the maintenance cost can account for up to 40 percent of the total production cost. Studies from 2001 have shown that one third of every US dollar in maintenance costs are wasted because the maintenance is either unnecessary or performed incorrectly. This is because the maintenance intervals has been based on statistical trend data or actual failures of components, but by monitoring the condition of equipment and components in the machines it is possible to prevent breakdowns and downtimes and optimize the repair intervals [8, p. 869].

A study made on 500 companies within diverse areas of operation has shown that using predictive maintenance methods will cut maintenance costs, reduce unscheduled machine failures, downtime, money tied up in spare parts inventory, and costs due to overtime. This resulted in a better production, longer machine life, a safer working environment, higher product quality and on the whole more profit. The total average maintenance costs were cut by over 50 percent, not including lost production time or variances in direct labor etc. Regular monitoring of the machine components reduced break downs by over 55 percent and the average time spent on repairs was reduced by 60 percent[8, p. 869].

The big savings were made since CBM made it possible for the industries to determine which components that had failed and made it possible for them to plan ahead for the repair. By knowing the need of equipment, spare parts, and knowledge of when the repair needs to be performed unnecessary costs and repair time could be avoided. CBM also made it possible to reduce the inventories of spare parts with over 30 percent, and even the operating life of the machinery increased by 30 percent[8, p. 870].

To be able to determine the condition of a component one will need to know the baseline (normal) condition and the trend of that specific component. When it is known how the component behaves and how the behavior changes over time it is possible to decide when the performance has reached an alarming level. Trending is the behavior of the equipment from baseline condition to shutdown. These five steps need to be followed to monitor the condition[6]:

- Define each major component
- List the parameters that need to be monitored
- Obtain baseline data
- Obtain trend data
- Establish threshold limits

Advantages of CBM are that the machine train becomes more accessible, the down-time decreases, the component lifetime increases, and this will lead to an increase in productivity [13, p. 810].

The tool most often used in condition monitoring is vibration measuring since this is the most effective tool for measuring the mechanical condition. To do a complete and successful condition monitoring other complementary techniques are used [7, chap 6]. These techniques can be; analysis of oil in hydraulics, tribological analysis (lubrication etc.), noise, wear and heat increase in the relevant components, process parameters, visual inspection, and ultrasonics.

3.2 Vibrations

The testing of vibrations started during WWII and has developed since then. Now it is present in many different types of industries from large structures to small microprocessors. From the start all the equipment was analog but gradually more and more were exchanged by digital monitors [9, Ch. 3 p. 2].

The difference between an online vibration measuring system and periodical measurements is that while a periodical measures e.g. 10 seconds every month leaving over 2 million seconds unsupervised an online system measures the vibration continuously. The benefits of measuring continuously are easy to understand when comparing the monitored time [16, p. 63].

Vibration measuring is the main condition monitoring technique used today and it can be applied to rotational, linearly moving or reciprocating mechanical equipment. Vibration measuring can be used for quality controls like detecting leaks or cracks, to analyze fluid flows, noise control and to detect loose parts [7, pp. 114–115].

To be able to interpret the results from vibration measuring it is essential to be able to separate the characteristic and the uncharacteristic vibration profiles. Not all vibrations mean that something is wrong, a shaft for instance is supposed to rotate. Problems in the machine, such as loose bolts, shafts that are misaligned, worn bearings, leaks and initial metal fatigue incipient, will however cause atypical vibrations [7, p. 121].

It is central to be aware of the cause of the changes in vibration amplitudes; it is not necessarily so that a decrease in vibration amplitude means better machine health and moreover will changes in operating conditions and load lead to a different vibration profile [7, p. 121].

In the book; An Introduction to Predictive Maintenance, p. 121, R. Keith Mobley stated the foundation of the methods for identifying and quantifying the root causes of failure;

- All common machinery problems and failure modes have distinct vibration frequency components that can be isolated and identified
- A frequency-domain vibration signature is generally used for analysis because it consists of discrete peaks, each representing a specific vibration source
- There is a cause, referred to as a forcing function, for every frequency component in a machine-train's vibration signature
- When the signature of a machine is compared over time, it will repeat until some event changes the vibration pattern

3.2.1 Sources of vibration

All forces acting on machines are not in equilibrium and this causes vibration. The signature vibrations are seen as peaks in frequency-domain plots [7, p. 122]. FFT (Fast Fourier Transform) is a method of converting a time based spectra to frequency based.

In rotating machinery the ideal condition would be such that all components are perfectly balanced and the center of mass is on the center line. This is however not the case and vibrations are caused by both rotating elements and unstable media flowing through the machine. If there is an unstable flow through the rotating machine it can cause the rotating elements to deflect from their true centerline. The flow can become unstable if operating conditions deviate from the conditions the machine is designed for. The impact on the vibration profile of flow through the rotating components is not as big as for load change, but it still creates a discernable peak in the FFT plot [7, p. 123].

Other problems in rotary machines can arise when the lift (rotors are designed to account for gravity and to center the rotating elements) generated by the rotor and the gravity is not in balance, or when a V-belt is stretched too tightly and the side load affect the load zone on the bearings [7, pp. 123–124].

In linear-motion and reciprocating machines there are more unbalanced forces present and their vibration profiles are discernable since the motion does not repeat itself with the rotation of the shaft. Reciprocating machines also cause a spike in the vibration profile when they change direction [7, pp. 124–125].

90 % of all vibrations are caused by unbalance, misalignment and resonance [16, p. 22].

Unbalance

Unbalance is the main reason for vibrations of large amplitudes. There are two types of unbalance; static unbalance and dynamic unbalance [17, pp. 14-17].

The definition of static unbalance is when the center of mass does not coincide with the center of rotation, and this can be detected by the help of gravity when the object is still and not rotating [17, p. 14].

In a thin round plate two different scenarios will cause static unbalance. The plate can be placed eccentrically on the shaft or the shaft can be bent. The plate can also be placed correctly on the shaft but can in itself have an unevenly distributed mass [17, pp. 14-15].

The definition of dynamic unbalance is when the plate is welded to the shaft in an angle. This can only be detected when the shaft is rotating. A plate of this character is said to have a center of mass on either side of the shaft that by centrifugal forces will bend the shaft and cause damage to the bearings [17, pp. 17-18].

Depending on cause, position, stability, resonance and type of unbalance the consequences will vary. There can be large unbalance forces present without causing large vibration amplitudes and at different conditions small forces can cause critical vibrations [17, p. 18].

Unbalance will show as vibrations in the same frequency as the rotational speed [17, p. 20].

Misalignment

Misalignment occurs when two consecutive shafts are displaced in relation to each other. It is the second most dominant reason for vibration damage in machines, but it is hard to detect. Two misaligned axes can cause wear in couplings, bearings, seals and gears. It can also cause bending and fatigue in the shaft, leakage of lubrication oil, foundation errors, play against foundation, heating and energy loss and elevated noise level [17, pp. 21-22].

One thing to be observant of is the fact that incorrectly mounted coupling halves can give the appearance of a misaligned machine [17, p. 22].

Reasons for misalignment are; poor assembly work on the machines, foundation errors, faults that develop with time in the feet of the machine, temperature changes, changes in loading and rotational speed and outer forces. The misalignment can be either parallel or angular [17, pp. 22-23].

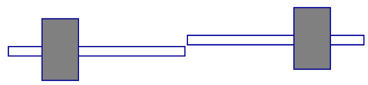

Figure 3.1: Parallel misalignment

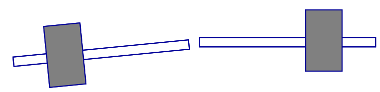

Figure 3.2: Angular misalignment

Misalignment can be detected with vibration analysis. An angular misalignment will give axial vibrations on the adjacent bearings with an oscillation that is displaced 180 degrees against the rotational frequency. A parallel misalignment will cause radial vibration with twice the rotational frequency in the adjacent bearings [17, pp. 25-26].

The vibration analysis gets complicated when the vibrations show combinations of different alignment errors, but the most common oscillation to monitor is the one with frequencies twice the size of the rotational frequency [17, p. 26].

A vibration analysis is recommended both before and after an alignment procedure [17, p. 27].

Critical Speed

All bodies have a natural frequency that is a function of the body's stiffness and its weight. The rotation or vibration of any body needs some sort of excitation to start and in rotors the excitation is mostly the torque or speed of the rotating shaft. The operating speed at which a rotor will be excited and a natural frequency will occur is called the critical speed [6]. This is the speed that will cause larger and larger oscillations until the body finally breaks.

There are different types of critical speeds; critical to bending and to torsion. In theoretical calculations the two are often separated [20, p. 342] but in reality most rotors are subjected to a combination of both. To minimize the risk of breakage the machine can be operated at a speed that is not near the critical speed. The stiffness and the weight of the rotor are important factors in determining the critical speed [5, p. 213] and these factors can be altered in an early stage of the development of the machine.

Faults in gearboxes

The purpose of a gear box is to transfer forces between axes. The cog that is carrying the forces at a specific moment will bend and then go back to normal when the next cog takes over. This will cause fatigue if there are faults in the gearbox [17, p. 38].

If there is something wrong with one cog it will cause a disturbance one time per revolution, damage on two cogs will cause disturbances twice per revolution and so on [17, pp. 38-39].

Vibration measurements can be done on the bearings or on the hoods that will amplify the noise. As a supplement to vibration analysis an analysis of the noise can be done. When a cog is damaged there will be a change in the level of vibration. If there is a crack in a cog this change will be very sudden and can even be a decrease in the disturbance-level amplitude [17, p. 39].

Even when the cogs are not damaged they will cause vibrations at z (number of cogs) times the rotational speed. This makes it important to compare the vibration spectra to the spectra from when the gear was new and to continuously trend data [17, p. 39].

A gearbox should last as long as the machine it is connected to but if it breaks down earlier it can be because of bad design, poor manufacturing, wrong size, unbalance, misalignment or poor lubrication [17, p. 42].

Faults in rolling bearings

Faults in ball- and roller bearings are caused by forces that pass the bearings from the inside out or forces from the surroundings. It can be; unbalance, misalignment, bent shaft, defect or incorrectly tightened belts, faults in an electric motor or gear, fluid impulses, incorrect mounting, plays, or poor lubrication. Vibrations can cause damage to bearings and already damaged bearings will cause vibrations [17, p. 45].

The large vibration amplitudes in a damaged bearing will only appear for a short while. If the bearing is worn to a big extent, the vibrations can decrease [17, p. 46].

Even when a machine with bearings is still, the bearings can be affected by vibrations in the surroundings. Cylindrical roller bearings are the most sensitive to vibrations and deep groove ball bearings the least [17, pp. 48-49].

High frequency vibrations can be caused by currents that can pass through the bearings in electrical drives. This is clearly visible in the form of dark ribs on the rolling elements and the ball race [17, p. 49].

Damage detection

When measuring vibrations it is important to be able to distinguish the vibrations that are caused by component damage from normal vibrations in a frequency spectrum. Especially with an incipient damage, the vibrations can be hard to discern from the background noise and to help with this problem several techniques are being used.

Scaling
Scaling is a way to zoom in on frequencies of interest. This can sometimes be done by using a log-scale. A big help in scaling is access to frequencies of bearings and to have them drawn as lines in the frequency diagram [17, p. 50].

Filtering
Normal vibrations from machines if often a multiple of the rotational speed and by filtering these frequencies out, the ones of interest become more discernable [17, pp. 50-51].

Envelop
Enveloping is used in computerized systems with sequential data collection. The theory is to move the frequency band to be analyzed to higher frequencies (maximum of 80 kHz) and in that way eliminate the normal vibration frequencies. Enveloping uses a broad frequency band from the shock pulses a damaged bearing causes. The analysis covers the area from basic frequency to the determined maximum [17, p. 52].

SEE
SEE is a method that is similar to Enveloping but moves the analysis to even higher frequency bands, up to 300-400 kHz, and utilizes an acoustic transducer to measure on the bearings. In lower frequency ranges there can become resonance between the source of the shock pulses and the measurement point, this is avoided with a higher frequency range. The measurements can be less reliable with this sensitivity and it can be wise to do more frequent measurements [17, pp. 52-53].

SPM
SPM - the Shock Pulse Method - utilizes a logarithmic scale to analyze shock pulse from damaged bearings. A single frequency is studied - the frequency where the measuring signal is amplified by the resonance of the transducer. This frequency is usually between 30-35 kHz and in this range there will often be resonances in the housing of the bearings. The SPM gives a value that has to be put in relation to when the bearing was new [17, pp. 53-54].

Today the SPM method is used primarily to detect damage and condition of lubrication in rolling bearings but it can also be used to identify misalignment, loose parts and cavitations. A shock pulse often begins in the area between the rolling elements and the inner or outer race. Since the surfaces are not completely smooth, they will cause shock pulses when two peaks hit each other or if the peaks do not break through the lubrication film they will cause variations in pressure in the lubrication. The shock pulses will spread from their origin to the bearing housing and further into the machine [32].

A thick lubrication film will cause less shock pulses, while metal against metal will cause the highest shock pulses. If there is damage in a bearing this will cause high and irregular shock pulses [32].

The parameters needed to do a shock pulse analysis are the bearing ISO number and the rotational speed. This will then give allowable values of a bearing in good condition. These are empirical values based on research and testing [32].

3.2.2 To identify the vibrations

To identify the source of a vibration in the FFT plot the frequency of the component's vibrations has to be known, and therefore the number of periodic peaks has to be known. A round wheel with an unbalance will cause vibration peaks one time per revolution, while a fan with four blades will cause peaks four times per revolution.

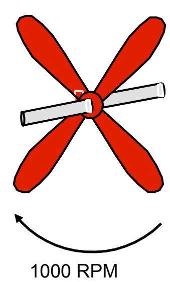

Figure 3.3: Four-bladed fan [D]

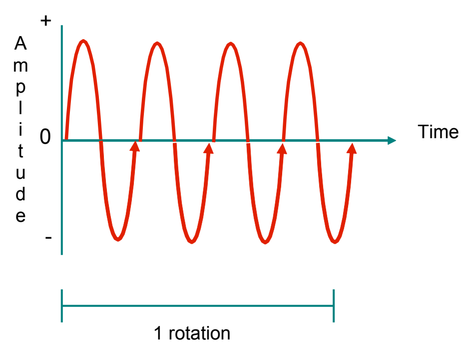

Figure 3.4: Time plot for fan [E]

If the fan rotates with 1000 rpm and the vibrations are 4 times per rotation it will be 4000 cycles per minute which gives a frequency of 4000/60=67 Hz.

When the plots from the time domain then are transferred to the FFT plots, it is easier to distinguish which component that is causing the vibration by looking at the amplitudes on different frequencies, see figure 3.5. Every peak in the FFT diagram is related to a certain fault in a machine part.

By providing a computer software with the vibration data, the rotational speed and other properties of the machine and its components, the software

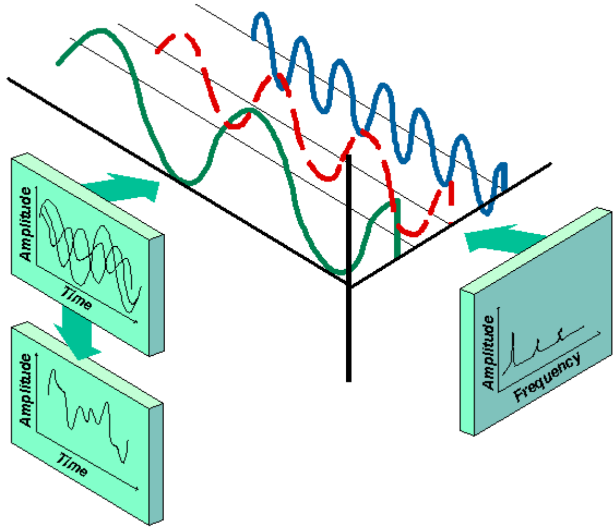

Figure 3.5: Transformation from time plot to FFT plot
[F]

will discern alarming levels of vibrations in different components [23].

One way to analyze the FFT spectra is for the software to calculate damage frequencies in the specific bearings and letting them show as lines in the spectra. In that way vibration peaks that coincide with the damage frequencies can be observed and the kind damage evident. In figure 3.6 is a spectra for a bearing with a first order damage frequency and its harmonics.

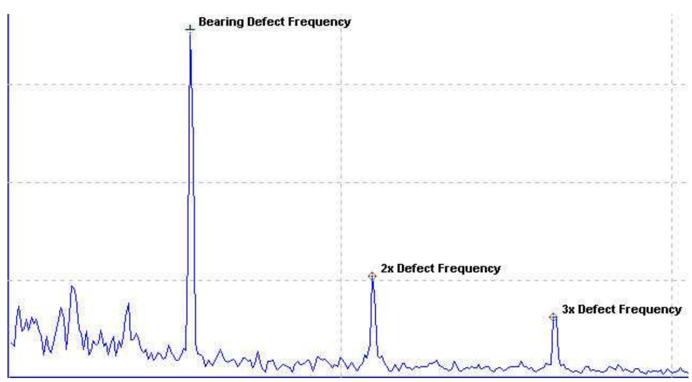

Figure 3.6: FFT plot with damage frequencies
[Q]

To illustrate how to calculate the frequency a damaged bearing will cause, an example with a rolling bearing with a pit is presented in figure 3.7.

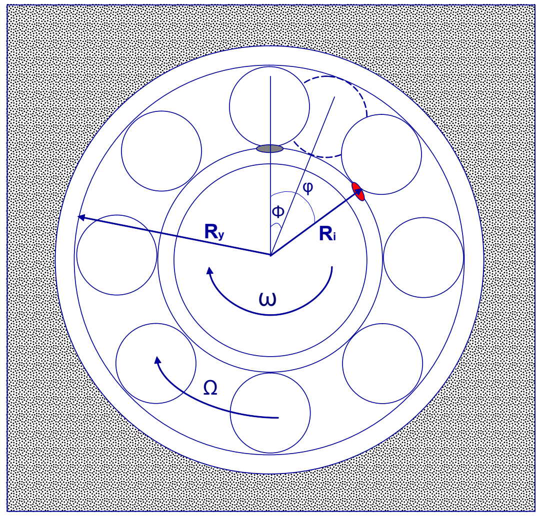

Figure 3.7: Rolling bearing with pit

Below is an explanation of the relationship between the rotational speed of the inner race, ω, and the rolling elements, Ω.

$$\frac{\omega - \Omega}{0 - \Omega} = -\frac{R_y}{R_i} \rightarrow \Omega = \omega\frac{R_i}{R_i + R_y} \rightarrow \Phi = \phi\frac{R_i}{R_i + R_y}$$

For a roller to hit the pit, and a peak to appear in the frequency spectra, the difference between the rotation of the pit on the inner race and the rotation of the rollers has to be equal to the angular distance between the rollers.

$$i\frac{2\pi}{z} = \phi - \Phi = \phi - \phi\frac{R_i}{R_i + R_y} = \phi(1 - \frac{R_i}{R_i + R_y}) = \phi\frac{R_y}{R_i + R_y}$$

$$\rightarrow \phi = i\frac{2\pi}{z} \cdot \frac{R_i + R_y}{R_y}$$

Here z is the number of rolling elements in the rolling bearing and $\frac{2\pi}{z}$ is the angle between two adjacent rolling elements. ϕ is the angle the pit has moved and Φ is the angle the rolling elements have moved. i is the number of times a rolling element will pass the pit and when the geometry of the bearing and the rotational speed are known, the frequency can easily be calculated.

Example

The deep groove ball bearing SKF623, with z=7, has an inner radius of 2.6mm and an outer radius of 4.1mm and with an inner ring rotational speed of 1000 rpm the frequency will be calculated as follows:

The inner ring will, every second, move an angle

$$\phi = \frac{2\pi \cdot 1000}{60}$$

In this time the rolling elements will have past the pit i number of times, that is:

$$i = \frac{z}{2\pi}\frac{R_y}{R_i + R_y}\phi \rightarrow i = \frac{7}{2\pi}\frac{4.1}{2.6 + 4.1} \cdot \frac{2\pi \cdot 1000}{60} \rightarrow i = 71.3Hz$$

If there would be two pits in the inner ring, the frequency would double, three pits would give a frequency three times as high and so on.

Similar calculations can be performed for damages on the outer ring or on the rolling elements themselves. Another alternative is to use SKF's homepage, choose the right bearing and provide the rotational speed and the frequencies will be calculated for you. Others ways to find out the damage frequencies are either to use formulas or approximate values.

There are four disturbance frequencies that can be calculated based on the rolling element diameter, bearing diameter and rotational speed. These frequencies are; Ball Pass Frequency Outer Race (BPFO), Ball Pass Frequency Inner Race (BPFI), Ball Spin Frequency (BSF) and Fundamental Train Frequency (FTF). BPFI is the frequency calculated in the previous example.

$$BPFO = \frac{z \cdot n}{2 \cdot 60}(1 - \frac{d}{D}cos\alpha)$$

$$BPFI = \frac{z \cdot n}{2 \cdot 60}(1 + \frac{d}{D}cos\alpha)$$

$$BSF = \frac{D \cdot n}{2d \cdot 60}(1 - (\frac{d}{D})^2(cos\alpha)^2)$$

$$FTF = z \cdot n(1 - \frac{d}{D}cos\alpha)$$

Here z is the number of rolling elements, d is the diameter of the rolling elements, D is the mean diameter and α is the contact angle [17, pp. 46-47].

If the bearing data are not accessible, the frequencies can be calculated approximately. BPFO and BPFI are often around 40 % and 60 % of z times the rotational speed, respectively and FTF will be almost half the rotational frequency [17, pp. 47-48].

In table 3.1 are some approximate damage frequencies for different machine components. Please note that the frequency unit is 1/s but in the table the unit is 1/min. All values therefore has to be divided by 60 to get the frequency value in Hertz.

Table 3.1: Vibration frequencies
[36]

Cause	Frequency	Amplitude
Less than 1 x rpm		
Beats	Different frequency	Comes and goes, caused by two machines running in almost the same speed
Oil whirl	Approximately 45% of rpm	Applicable to high speed machines with plain bearings
Looseness	0.5, 1.5, 2.5 x rpm etc	Applicable to high speed machines with plain bearings
Belts	π x (rpm) x (pitch diameter)	Note: Strobe light helps to see the defect
Resonance	Discrete peaks	A serious condition with very high amplitudes
At 1 x rpm		
Unbalance	1 x rpm	Mostly radial; a common fault
Misalignment	1 x rpm + harmonics	High 2x and 3x; high axial; a common fault
Eccentricity	1 x rpm	Looks like unbalance, cannot be corrected with weights
Bent shaft	1 x rpm	Looks like unbalance, can be corrected with massive balance weights near the center
Soft foot	1 x rpm	Dramatically decreases by loosening one hold-down bolt
Medium frequencies		
Misalignment	2x, 3x + harmonics	High axial; changes with temperature, common fault
Motor (electrical)	2 x (Mains frequency) + harmonics	Stop immediately upon disconnecting power. Also causes 2xMains frequency Hz sidebands at higher frequencies. Usually not destructive but indication of the quality of construction. Present on all motors and transformers to some degree.
Looseness	0.5, 1.5, 2.5 x rpm etc	Decreases with load
Bearings	FTF - 0.4 x rpm BPFO - 0.4 x rpm x z BPFI - 0.6 x rpm x z z - no. of balls	High frequency shock pulses in time domain
Blades	rpm x (no of blades)	Benign
High frequencies		
Gears	rpm x (no of teeth)	Sidebands at gear mesh frequency; 2x gear mesh usually larger
Cavitation	3-5 kHz broadband	Usually benign; pressurizing inlet helps
Bearing	Broadband	High frequency shock pulses in time domain

3.2.3 Data acquisition

One of the most important things when using vibration analysis is to have accurate and repeatable data. To be able to use the data in a predictive maintenance program it is of great importance to keep a good record of historical key parameters to be able to compare the data to identify changes. For the measurements to be completely repeatable it is important that the measurements are performed at exactly the same point and in the same way every time, this can be facilitated by permanently mounting the transducer at the measuring point [7, p. 152].

Equipment for measuring vibrations

To measure vibrations online in machines, transducers are placed at locations of interest. The typical transducer used is the accelerometer with piezoelectric films that converts strains or compressions into electrical signals that can be measured [7, p. 121].

A portable vibration analyzer can be used to collect and store the data from the transducers, convert it and perform a Fast Fourier Transform. The instrument itself can be programmed to set of alarms and display data, but it can also transfer the information to a computer for more refined functions and analyses [7, p. 121].

When using portable vibration measuring equipment the vibrations are measured in three directions; horizontally, vertically and axially by attaching an accelerometer with a magnet to the desired measuring point. The entire equipment is then taken back to the office to transfer and analyze the data collected.

Mounted transducers with a portable vibration analyzer can be called a semi-online system.

A system that is fully online consists of mounted accelerometers that are connected to units that continously or on triggers will transfer the collected information to a computer with an analyzing software.

Vibration detectors

There are many ways of measuring vibrations and even more transducers to choose from. There are however three major types of vibration transducers, measuring; displacement, velocity and acceleration [7, p. 152].

Displacement transducers

Displacement probes measures the movement of for example a shaft in relation to the probe, the result is often recorded as a peak-to-peak value which represents the maximum displacement [7, p. 153]. Displacement probes can be used to measure radial vibrations and axial displacement in rotating machines or valve positioning. When accelerometers can not be used in rotating shafts, displacement probes can be used instead[24]. These probes are most useful in the frequency range from 10 to 1000 Hz. The cost of installing displacement probes is relatively high and therefore they are usually installed at key locations first [7, p. 153].

Eddy-current transducers
Eddy-current sensors are ideal for measuring vibrations because of their good frequency response, lack of mechanical loading and noncontact operation. Eccentricity of rotating shafts and looseness of bearings are other fields where these sensors can be useful.

An eddy-current is generated by a coil that is driven with an alternating voltage, the coil creates an electromagnetic field if there is an electroconductive object close to it and that field induces eddy currents. To measure the distance to the object the coil impedance is measured. This is possible since the eddy currents produce an electromagnetic field which opposes to the original field and can change the inductance of the coil [4, Ch 14, p. 9].

Velocity transducers
Velocity transducers monitor both relative and casing vibrations. The output from the transducers is the rate of displacement and not the distance of the movement that was the case with displacement probes. What they have in common is the frequency range that is 10 to 1000 Hz for velocity transducers too.

Velocity transducers are very sensitive to mechanical and thermal damage and they are also in need of having strict recalibration programs. The risk of data being incorrect is high if the calibration is not performed in a correct way [7, p. 154].

Accelerometers
The best way of determining the force that vibrations practice on a machine is to measure the acceleration. Accelerometers often use piezoelectric crystals to convert mechanical energy to electrical signals [7, p. 155]. The normal frequency range for an accelerometer is 1 to 40 000 Hz [25] but there are ultrasonic accelerometers that can measure frequencies up to 1 MHz. The piezoelectric crystals are sensitive to thermal heat and may be damaged if they are subjected to heat for too long[7, p. 155].

Piezoelectric
Piezoelectric elements are crystals that have the ability to convert mechanical stress to electricity when they are elongat ed or compressed; this is called the

direct piezoelectric effect. Reverse piezoelectric effect is piezoelectric elements ability to convert electricity to mechanical stress. The direct effect is the one used to sense forces, torques and pressures on the elements and thereby sense relative displacements. The strain in the piezoelectric elements is brought on by a seismic mass and its internal force.

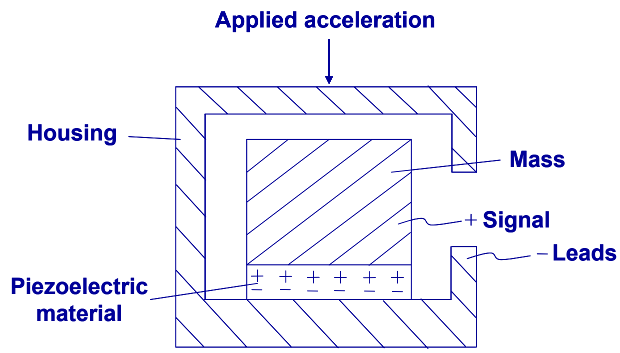

Figure 3.8: Piezoelectric accelerometer
[I]

A common material used in acceleration sensors is quartz because of its desirable properties; it offers good repeatability and is stable both over time and thermally [4, Ch 14, pp. 25-30].

Multiaxial accelerometers
Piezoelectric, piezoresistive and capacitive accelerometers can all be used in multiaxial accelerometers, which are used when it is necessary to measure the acceleration at one point in an orthogonal coordinate system. Two different systems for doing this are used; the multiaxial arrangement of monoaxial accelerometers and the intrinsically multiaxial accelerometers. The multiaxial arrangement of monoaxial accelerometers contains of up to three accelerometers placed in different directions and the intrinsically of up to three orthogonal sensors in one single housing. The latter has the benefits of being lighter, easier to install, it does not worsen the high-frequency response and it does not consume a lot of space. The downside would be that it is more expensive [4, Ch 14, pp. 34-35] and that it does not meet the requirements in the ISO standard for vibration measurements according to the sales engineer from SPM.

How to mount the accelerometers

The weight of rotating parts is most often supported by bearings that usually bear large forces. They are often damaged or worn out and they show early symptoms and this makes bearings a good subject for condition monitoring

[31, p. 30].

The way the accelerometer is placed is of huge importance since an incorrect placement of the accelerometer strongly affects the accuracy of the readings.

Important things to remember are to put the accelerometers as close to the bearings as possible and it should be on the centerline of the bearings for the signals not to be distorted. Another thing is to make sure that the accelerometer is attached so that it does not move independently and produces distorted signals. To make sure that it is securely attached it should measure on an even surface with no dust or other larger particles. If the head of the accelerometer is magnetic, i.e. if the way to attach it to the measurement point is with a magnet, it is important that the area is fully magnetic and not a surface of non-magnetic material with magnetic material underneath. It is also important that the accelerometers magnetic properties are not lost because the magnet is dropped or heated [31, pp. 30-33].

How to mount the accelerometers depends on what vibrations that needs to be monitored. If the parallel misalignment is to be measured, the accelerometer should be mounted in radial direction of the bearings and when studying angular misalignment the axial direction should be chosen. The reason for the importance of picking the right direction is that the vibration amplitude will be different in different directions [31, p. 34].

According to the suppliers of CBM systems, when installing an online CBM system there is usually only one sensor placed in one direction on every measuring point, whilst when doing the measurements manually all three directions are measured, that is; horizontally, vertically and axially. In online systems the most sensitive direction is detected and the sensor is then placed in that direction. This is sufficient since the sensor is permanently and firmly mounted.

If manual instruments are used it is important to measure on the exact same location on the component at every monitoring exercise. It is also central that the vibration measurement is done on a stable structure; a good rule is that the weight of the accelerometer and the magnetic mounting together should be less than 10 % of the weight of the vibrating structure [31, p. 35].

To avoid a peak in the vibration spectrum care must be taken when placing and removing the accelerometer on the surface. The best way is to tilt the magnetic head. It is also important that cables are not twisted and can not swing freely [31, p. 36].

Perhaps one of the most important factors to consider when performing vibration analysis is the safety.

Some risks are more prominent than others; injury from moving parts, electrical shock and magnet induced damage. The cable can get caught in moving parts, the magnet can destroy items that are sensitive for magnetic fields like floppy discs, watches etc and if the accelerometer is attached to high voltage surfaces there is a risk for electric shock [31, p. 37].

Choice of accelerometer

When choosing accelerometer for a certain application several factors have to be taken into account.

- Measuring range
- Sensitivity
- Resolution
- Dynamic range
- Frequency response
- Environmental factors
- Mass loading effect
- Cost

[4, ch. 14, pp. 35-38]

Vibration analysis techniques

Trending
When monitoring vibrations the variations over time are of great interest. To be able to evaluate the results the vibration data needs to be normalized to remove the influence of load, speed etc. If the level of the vibrations changes, this is a sign that the operating condition has changed. The value of saving historical data is very high when using this technique [7, p. 161].

Broadband
Broadband analysis measures the overall machine condition by measuring the vibrations. The wide range of vibrations that are recorded prevents the technique from being used to pinpoint the specific problem in the machine. It is however a good tool to analyze long term trending of the overall condition in the machine [7, p. 162].

Narrowband
Narrowband analysis has the same function as a broadband analysis but has the advantage that the user can specify the frequency range that is measured.

This makes it possible to identify specific components that might be of interest [7, p. 162].

Comparative analysis
The objective of comparative analysis is to compare two or more data sets to detect changes in the vibration level and by that detect changes in the operating condition. Since the only output from the analysis is the change in vibration level, this is not the right method to use if the actual level of vibration is of interest [7, p. 162].

Signature analysis
All machines have a unique vibration signature that can be broken down into peaks where every peak represents a specific component in the machine. If this is possible to do it is a powerful analysis tool to be able to monitor the overall machine condition by monitoring the specific parts. The downside with this technique is that it requires a lot of microprocessor memory. Signature analysis is only beneficial if there is a confirmed problem in the machine that needs further investigation[7, p. 165].

The resolution of broadband analysis is too low for it to be effective in signature analysis; narrowband on the other hand is a good choice of analysis method in this case because of the possibility to choose the measuring range. Machinery problems are usually detected near one of the running speeds and the narrowband can be preset to monitor a specific range of vibrations [7, p. 165].

3.3 Ultrasonics

Both vibration and ultrasonic analysis are a way of detecting noise and sound, the only difference is the frequency they detect, vibration analysis is used up to 30 000 Hz and ultrasonic is used from 30 kHz to 1 MHz. Ultrasonic measurements have three main applications within the predictive maintenance area; leak detecting, material testing and airborne noise analysis [7, p. 256].

3.3.1 Applications

Airborne noise analysis

The primary goal of measuring the airborne noise is to protect the hearing and health of the people working near the machine or plant. The instrument used is mostly an ultrasonic meter and it can be used to detect unusual noise emissions from the machine. However the measurements can not be used to determine any root cause of the noise [7, p. 256].

Material testing

When testing materials to detect flaws and cracks ultrasonic is the primary method. The test is fairly simple and consists of introducing an energy source into the measured material and by using ultrasonic instruments measure the response of the material. The technique behind the measurements is based on the emission and reception of the signals. The amplitude and strength of these signals are measured and the fact that different materials can transport vibrations and waves at different speeds are taken into consideration. The interface between for example steel and air alters the amount of vibrations that are reflected. When reaching a steel/air interface 99.9 % of sound vibrations are reflected. By detecting how much of the vibrations that are reflected and the time for the reflected vibrations to return the size and locations of cracks can be determined. If the crack is very small or not open it is not detected by the ultrasonic measurement [7, p. 257].

Leak detection

When liquids and gases pass through a small crack the turbulence produces a high frequency sound that can easily be detected by using an ultrasonic instrument. This application is the most common for ultrasonics and the technique is ideal for detecting leaks in piping, valves and other process systems [7, p. 257].

3.3.2 Types of ultrasonic systems

When using ultrasonics as a method of predictive maintenance there are two systems that are used, one of them measures airborne sound and vibrations and the other measures structural vibrations. The airborne ultrasonic detectors are mostly used to detect gas pressure leaks, the fact that they detect the sound of the leak and not the gas itself makes it more versatile than many other gas leak detectors. The airborne detectors can also be used in a contact mode where a metal rod is the contact element with a surface that is subjected to vibrations. This method is mostly used to detect restrictions in process piping.

Some ultrasonic instruments can be placed inside pipes to be used as quick check instruments of tank seams, seals or hatches or to check building wall joints.

The cost when using ultrasonics is relatively low and that is because most of the monitoring systems only work as scanners where the user has to interpret the results and store the data. When they are used to detect leaks the required training is low since the technique is very simple. The low cost, potential of finding leaks in a plant and the little training required are reasons for using ultrasonic measuring in a predictive maintenance program [7, p. 258].

3.3.3 Limitations

Many ultrasonic systems are marketed and sold as instruments of monitoring the condition of bearings. This is however not possible with ultrasonic instruments and require a more sophisticated vibration analysis [7, p. 258].

3.4 Thermography

Thermography is the technology that makes it possible to detect infrared energy, that all objects with a temperature over absolute zero emits, e.g. heat, without having any contact with the element of interest. With special cameras that can discover the infrared energy, and make it visible to the human eye it is possible to notice changes in heat and thus areas where something has gone wrong [26].

Below is a picture of what a fault in an industrial electric fuse box can look like.

Figure 3.9: Thermography
[N]

3.4.1 Applications

The technique of thermography is often used in industrial environments when probes or thermocouples cannot be used e.g. for measuring moving parts, parts surrounded by an electromagnetic field or vacuum, or when a fast response is needed [27].

Areas where it might be useful to use termography are areas relying on heat retention or transfer such as; electrical switchgears, gearboxes, electrical substations, transmissions, circuit breaker panels, motors, and bearings [7, p. 107].

What happens in thermography is that a lens focuses the infrared energy onto a detector; the detector converts the IR energy to a signal which can be read as temperature. This electric signal is also compensated with respect to the ambient temperature [27].

3.4.2 Types of thermography

The three types of thermographical instruments most often used when monitoring a machine's condition are; infrared thermometers, line scanners and infrared imaging.

Infrared Thermometers

Infrared thermometers are typically used, when a vibration instrument has found a critical area, to measure the surface temperature at a single spot. They are also called spot radiometers. Typical areas of use are on bearing caps, motor windings and process piping [7, p. 106].

Line Scanners

Line scanners offer a scan in one dimension (a line) of radiation. Even though it gives a slightly wider view of the temperature difference on a surface, it is limited when monitoring machine condition [7, p. 106].

Infrared imaging

Infrared imaging is a quick way to examine the infrared emissions of a whole machine, equipment or process. The way it works is similar to a video camera; by looking through the optics a thermal emission profile can be seen [7, pp. 106–107].

3.4.3 Limitations

Nevertheless the technology of measuring objects infrared emissions is not a straight forward process; objects do not only emit but also absorb and transmit infrared energy. Because of the fact that the information needed to monitor the condition of the object is the energy emitted, the other two energies have to be filtered out before the analysis can begin. Another factor that has to be taken into account is the atmosphere in-between the object to be measured and the measuring instrument. There are gases that absorb infrared radiation, like for instance water vapor and there are particles and light that can distort infrared radiation, and to minimize the negative consequences of the atmospheric conditions there are filters to be used. These filters however are different for different conditions, which makes it important for the operator to know what filter to use depending on the condition [7, p. 105].

There are factors that affect how much infrared energy an object emits, such as; different surface conditions and coatings of paint or protective surfaces and to be able to take this into consideration there are tables of emissivity for most materials [7, p. 173].

3.5 Tribology

3.5.1 Rolling bearings

Different designs of rolling bearings are suited for different purposes and environments. Roller bearings can carry higher loads than ball bearings [19, pp. 211-214].

It is usually difficult to predict which bearing to use, since many different load cases can act on one bearing and the space available has to be accounted for as well. Another factor that can be taken into account is the noise level allowed [19, p. 211].

The allowable operating temperature sets limitations to the rotational speed of the bearing; the bearings with the lowest friction are the ones that can handle the highest rotational speed [19, pp. 211-214].

There are several more parameters that need to be decided when the decision of which bearing to use is made; size of bearing, temperature, rotational speed, lifespan, lubrication conditions and risk of pollution in lubrication[19, pp. 217-218]. The forces in rolling bearings are transferred in the contact between rolls or balls and rings, and the volumes that have to carry the majority of the load are less than a thousandth of the total material volume [19, pp. 217-218].

Lifespan

Calculation of the lifespan of a bearing is done theoretically and only gives a mean value. Some bearings can break earlier and some later depending on the composition of the bearing. When bearings are casted and molded inclusions of waste products will end up at different locations in the body. The bearings with inclusions in the volume that carry the greater part of the load will have a shorter lifespan than those with inclusions in the body where the stresses are low [19, pp. 217-218]. To get an idea of the distribution it can be said that the median lifespan is approximately five times as long as the nominal (L_{10} is the lifespan that at least 90% of a large amount of bearings, of the same type, is expected to have). The definition of lifespan is the hours of operation with a constant rotational speed or number of rotations a bearing will last before signs of fatigue show[19, p. 224]. When calculating the nominal value of the lifespan, the load is accounted for as follows:

$$L_{10} = (C/P)^p$$

Where C is the radial load that would lead to fracture after 1 million rotations, P is the equivalent dynamic load on the bearing and p an exponent that is 3 for ball bearings and 10/3 for roller bearings. P is calculated as: P= $XF_r + YF_a$, F_r is the radial load and F_a is the axial load on the bearing, X and Y are factors depending on which bearing that is used and the fraction F_a/F_r [19, p.224]. This formula is based on experience and factors such as lubrication, but to get a more accurate result, more variables can be of interest[19, pp. 228-241].

The lifespan formula has been modified a few times as materials and the precision in manufacturing has improved. When there were not inclusions in the material to the same extent as before; the importance of clean lubrication films became prominent. Therefore, a new factor called a_{SKF} was introduced. In the new formula the variation of the stresses is taken into account and the mean values are no longer used; to do predictions of the strength of a bearing the strength and the stresses at one point have to be compared. The value of a_{SKF} depends on; the relationship between the viscosity of the lubrication film ν and the required viscosity at the operating temperature ν_1 (the relationship $\kappa = \frac{\nu}{\nu_1}$), P_u which is the load that would give the bearing eternal life if the lubrication is clean, and η_c which is a factor that describes the level of cleanness e.g. the level of solid contaminants. η_c varies between 0 and 1, where 1 means very clean and 0 means very contaminated[19, pp. 228-241].

$$L_{mn} = a_1 a_{SKF} L_{10}$$

If κ were to be less than 1 a lubrication containing EP additives can prolong the lifespan of the bearing to be (4-3κ) times L_{mn} maximum. What the additives do is that they help the surfaces to wear in and make them smoother, which means that less lubrication film is needed to separate the surfaces. There are limitations to using this factor when calculating the life span; it should not be used if the lubrication film is not clean e.g. η_c is less than 0.5, or if $(4 - 3\kappa)a_{SKF}$ is higher than the value of a_{SKF} when κ=1 [19, pp. 228-241].

The degree of impact the solid contaminants in the lubrication film has on the lifespan is dependent on the conditions of operation, system of lubrication and whether or not the film is filtered and cleaned. These parameters control the size of the bearing, the thickness of the lubrication film, the number of solid contaminants, their size and how hard or soft they are[19, pp. 228-241].

There are several ways of assessing how big of an impact the contaminants have on the lifespan of a bearing, the most reliable one being to study the depressions the contaminants cause on the surfaces that carry the load. It is possible to see the increase in stress by counting the number of depressions and examining their geometry, an increase in stress would reduce the value of η_c and consequently give a shorter lifespan. Another method is to, with an oil sample and electron microscope, study the composition of the material and the hardness of the contamination particles. With this information the contamination factor can be calculated. This is the second most reliable way of assessing the impact of the contaminations[19, p. 245].

Forces in bearings

The reason for bearings breaking is often that they are subjected to disturbance forces on the axis they are carrying.

If an axis with a centric mass is subjected to the disturbance force Q, each of the bearings will be subjected to the force 0.5F, where F is the force acting on the axis from the mass.

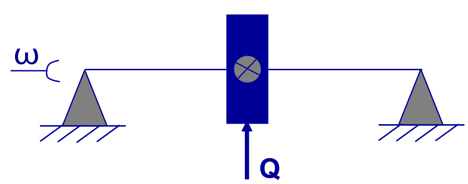

Figure 3.10: Axis and mass subjected to a disturbance force

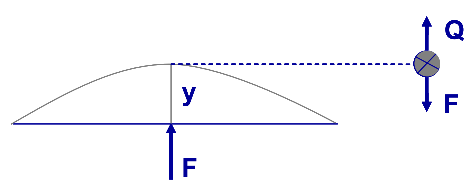

Figure 3.11: Axis and mass subjected to a disturbance force

In a fixed system the equation of motion will be:

$$m\ddot{y} = Q - F$$

Where

$$y = \alpha F$$

This will give

$$m\ddot{y} + \frac{y}{\alpha} = Q \rightarrow \ddot{y} + \frac{1}{\alpha m} y = \frac{Q}{m}$$

The solution to the homogeneous solution will give the resonance speed ω_e

$$\omega_e^2 = \frac{1}{\alpha m}$$

and the final equation will be

$$\ddot{y} + \omega_e^2 y = \frac{Q}{m}$$

If the disturbance Q is a periodical force where Q_0 is the amplitude of the disturbance and qw is the disturbance frequency (q= number of disturbances per revolution) the equation will read:

$$\ddot{y} + \omega_e^2 y = \frac{Q_0 sinq\omega t}{m}$$

The solution to this differential equation is

$$y = Asin\omega_e t + Bcos\omega_e t + \frac{Q_0 sinq\omega t}{m(\omega_e^2 - q^2\omega^2)}$$

This means that the forces in the bearings (0.5F) are equal to

$$\frac{F}{2} = \frac{y}{2\alpha} = \frac{m\omega_e^2}{2}(Asin\omega_e t + Bcos\omega_e t + \frac{Q_0 sinq\omega t}{m(\omega_e^2 - q^2\omega^2)})$$

Since the homogenous solution will become damped in steady state (when consideration is not taken to the start-up condition of the system) the only term left is the contribution from the disturbance. The disturbance is the interesting parameter to measure to investigate damage in components. The forces in the bearings will only depend on the amplitude of the disturbance force and the disturbance frequency. A high disturbance amplitude or disturbance frequencies that are in the range of the natural frequency will give high bearing forces, whilst very high or very low disturbance frequencies will reduce the load on the bearings. This can be explained intuitively; a pulsation can not cause as high of a force if more energy is required for the back and forth movement. If the disturbance amplitude is relatively large the disturbance frequency does not need to be close to the natural frequency for a damage to be detected.

3.5.2 Wear

There are five types of wear that can affect machine parts that are in contact with each other; rolling fatigue wear, severe sliding wear, rubbing wear, cutting wear and combined rolling and sliding wear. These different types of wear can appear on their own or in combination with each other [7, p. 205].

Rolling fatigue wear

Rolling fatigue mostly occurs in rolling contact bearings and is caused by the tensile stresses that a surface is subjected to when another surface rolls over it. The stresses can cause pitting in the surface, pitting is small holes in the surface. The wear particles can pass through the rolling contacts [7, p. 206]. The particles and the pitting can change the vibration pattern of the component, this can be detected when measuring the vibrations.

Severe sliding wear

When a gear system is subjected to high temperature or stress the surfaces are in high risk of wear. Large particles can break away from the surface and cause even more wear. This type of wear can have highly damaging effects [7, p. 206].

Rubbing wear

When parts of a machine are sliding against each other the result may be rubbing wear if the lubrication is not sufficient. Rubbing wear rarely causes catastrophic break-downs but the wear out rate may be high. The result of rubbing wear is caused when the thin layer of strong material that is created on the surface during the break-in period of the machine is damaged or not as effective as it can be, or if the generation of this thin layer is slower than the wear. If a new layer is not generated before the old one is worn down both the wear rate and the size of the particles increase. The rate of rubbing wear increases if the lubrication system is contaminated [7, p. 206].

Cutting wear

If a hard surface is misaligned or is damaged it may cut in to a softer surface causing cutting wear particles. If these particles appear in a system they are a sign that something is wrong and something needs to be done to prevent more damage. The cutting wear particles can be embedded in the softer of the two surfaces and cause damages on the opposing surface. If the particles are small they are probably the result of contamination of the lubricant but if they are large that is a sign that one or more components are on their way to failure [7, p. 206].

Combined rolling and sliding wear

If the speed or the load is too high in a gear system the result may be combined rolling and sliding wear on the moving parts. Tensile stresses on the gear surface can cause fatigue cracks that spread and cause pitting. The rougher the surfaces become the more the wear rate increases. The process generates heat that can damage the lubricant [7, p. 206].

Analyzing the amount, size and shape of wear particles in a lubricating oil system gives information about the wearing condition in the machine. As mentioned above different types of wear produces different types of wear particles and an analysis of the particles found in the lubrication oil can determine what type of wear exists in the machine [7, p. 206].

Lubrication oil

If the oil is contaminated with particles, water or anything else that does not belong in the lubricant the performance of the lubricant decreases and the risk of wear increases. There are several different methods of examining the lubricant oil; a few of them are ferrography, spectrometric oil analysis, chromatography and particle count [7, p. 203].

Ferrography

At first ferrography was a technique using magnets to separate only the magnetic particles from the lubrication but it has progressed and now it is possible to detect and precipitate both magnetic and non-magnetic particles. When the particles are discerned, besides being counted they are analyzed in microscopes to determine the size, composition, shape and texture [28].

There are three main types of equipment that are used in Ferrographic analysis; the Direct-Reading Ferrograph, the Analytical Ferrograph System and the Ferrogram Scanner (scanning electron microscope) [28].

The Direct-Reading Ferrograph is an instrument that separates particles from the lubrication oil to the bottom of a glass tube where a magnetic field is applied. Light is headed at two positions where the permanent magnet has discerned the large and the small particles and this gives two readings; Direct Large for particles over 5 microns and Direct Small for particles below 5 microns. These two values added together and then divided by the volume of the sample gives the Wear Particle Concentration [28].

The Analytical Ferrograph stores the wear sample and the information from the analysis in a permanent record. In that way it is easy to make out wear patterns of particular pieces of equipment. Beyond this it is also used to set up for a ferrogram; preparing a slide with wear particles to be analyzed and documented [28].

Spectrometric oil analysis

There are two types of spectrometric oil analysis; Emission Spectrometry and Atomic Absorption Spectrometry with the purpose of quantifying the dissolved and atomized contaminant particles in lubricating oil. The two methods both utilize the technology of detecting the wavelength of the light that an atom absorbs when excited or emits when returning to the ground state after being excited. These wavelengths are either in the visible or the ultraviolet region of the energy spectrum and they are characteristic for each impurity [29].

In Emission Spectrometry the atoms are excited by high voltage and particularly the metallic impurities emits light that is spectrally analyzed[O].

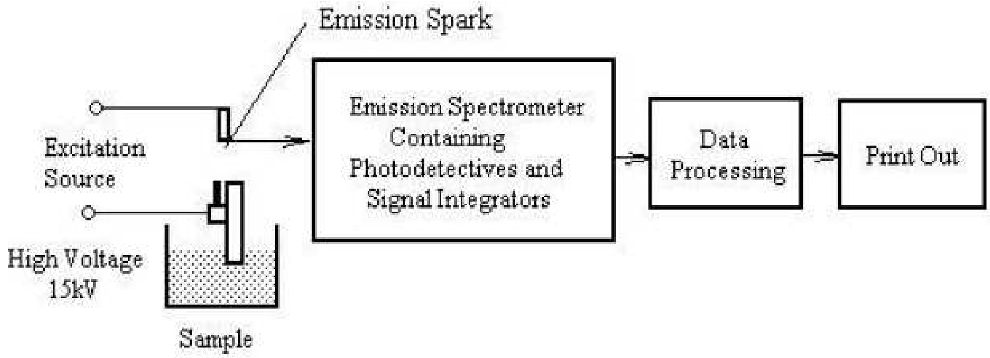

Figure 3.12: Emission spectrometer
[O]

The Atomic Absorption Spectrometry is very similar but instead of the atoms being excited by high voltage an oxyacetylene flame is used. This atomizes the metallic atoms and the absorbed wavelengths are detected[O].

Chromatography

There are several different kinds of chromatography, but what they all have in common is that they separate and analyze chemical compounds in a medium. This is done with the help of two phases; one mobile and one stationary between which the substances of interest are distributed. The phases can be solid, liquid or gaseous. Some chemical compounds thrive in the stationary phase and will dilute rapidly into the stationary phase. Others will travel with the mobile phase longer and by measuring when the compounds dilute it is possible to discern different kinds of dilutions [30].

Coast-Down Time (CDT)

The definition of Cost-Down Time is the time it takes for a rotating system to come to a complete stop after the power supply has been cut. This time will depend on the tribology conditions, inertia forces, the components in the system, mechanical conditions, and the surroundings. It can be used for controlling the condition, quality and maintenance of different components and is especially useful for measuring the conditions of the lubrication [13, p. 810].

The reason for investigating CDT measurements is that vibration measurements not always can determine the root cause to a problem in a system

[13, p. 810].

What is done in the CDT measurements is that the rotational speed of the system is plotted against the CDT. These curves are made; one when the system to be measured is new and then continuously during the lifetime of the components to be able to compare them to each other and determine the causes for malfunctions and weakening of the components. By using CDT together with vibration measurements, it is possible to find faults and deterioration with higher accuracy [13, p. 810].

Diluted oil decreases the Coast-Down time and increases the amplitude of the vibrations; this is because of the contaminants in the oil and the oxidation that becomes when the oil has been used for some time. Another factor that will give a deviant CDT curve and higher amplitudes of vibration is force imbalance. This demonstrates that the tribological behavior is affected by the mechanical [13, p. 816].

3.6 Hydraulics

The use of liquids to transfer mechanical forces is called hydraulics. Hydromechanics is divided into two areas; hydrostatics and hydrodynamics where the first is using slow movement of the liquid but large pressures and the second uses fast movement and low pressure. The high pressures in hydrostatics can be translated into large amounts of power and because of that this technique is often used in heavy machinery.

The temperature of the liquid affects the properties of the liquid and too hot liquids can damage components[18].

3.6.1 Hydraulic liquid

The most commonly used liquid in hydraulic systems is mineral based oil.

The viscosity of a hydraulic oil is one of its most important properties. There are two types of viscosity; dynamic and kinematic. The dynamic viscosity is defined as a liquids ability to resist shear stress. The dimension of this viscosity is [kg/(s·m)]. The kinematic viscosity describes how fast a fluid will spread, in relation to its mass, if it is poured on a flat surface. The dimension of kinematic viscosity is [m^2/s] [18, Chap 7].

The viscosity of oils decreases with temperature which means that they become more fluid with higher temperature. High viscosity means better lubrication and less leakage but large fluid losses. When choosing a hydraulic liquid it is important to know where it will be used, as mentioned, the temperature has a big influence on the characteristics of the fluid. There is no natural fluid that has all the wanted properties and those liquids mostly used have additives to get the right combination of properties.

3.6.2 Applications and limitations

There are three major causes for a hydraulic system not to run smoothly; the operating condition, the contamination level and the temperature of the system. The operating condition is often hard to influence since the system is designed to operate in a certain way.

The temperature is a result of the operating condition and a change of temperature is an important signal that something could be wrong. When monitoring the temperature it is important to know the normal operating temperature. To know the temperature is also important when choosing the hydraulic liquid since the properties of the liquid changes with the temperature as mentioned before. If the temperature is too high the leakage increases, the lubrication is not as good and the lifespan of the hydraulic liquid is decreased. If the temperature is too low, on the other hand, there might be a drop in pressure and because of that cavitation.

The contamination level is a combination of a few different types of contamination. The most important are: solid particles generated by wear and erosion, soft particles generated by the hydraulic liquid and there can be air or water in the liquid that increases the wear. To control the level of contamination a filter can be used, the filter can have an indicator that signals when the filter needs to be cleaned or changed. To continuously take samples of the liquid and analyze it is another way of detecting contamination of the oil. This can be done either manually or automatically within the system [15, p. 109].

3.7 Motors

The motors used in the printing units in VT Flex 175 ES are asynchronous servo motors. The same type of motors are used in the extruders in the laminator.

3.7.1 Asynchronous machines

Most electrical motors are asynchronous. Their popularity comes from being simple, inexpensive, reliable, standardized and cheap to maintain [11, p. 362]. The most common way to modify the rotating speed of an asynchronous motor is to change the frequency of the supply voltage. Frequency converters are used to change the frequency in a controlled manner [11, p. 368].

An asynchronous motor consists of a rotor and a stator. The rotor has electrical windings that are connected to each other and shorted. The power is transferred to the windings by induction from the stator. The winding consists of rods joined in the ends by rings, because of the way the winding looks this machine is sometimes called squirrel cage machine [11, p. 362].

The rotation of the rotor is complex and will not be further developed in this report.

3.7.2 Servo motors

Servo motors are electrical motors that can be controlled by electrical pulses. The output shaft can be positioned with the use of short pulses and they maintain their position until told otherwise. This feature makes them useful in applications where controlling the position or the speed is important [34].

Servo motors use a feedback system to position themselves; the desired position is subtracted from the actual position and if they do not correspond a signal is sent to the motor to move until it reaches the desired position [10].

3.7.3 Faults in electrical motors

There are many reasons for an electrical motor not to function perfectly, according to an article in International Journal of Systems Applications, Engineering & Development [21] the main reasons are:

- Stator faults resulting in the opening or shorting of one or more of a stator phase windings
- Abnormal connection of the stator windings
- Broken rotor bar or cracked rotor end rings
- Static and/or dynamic air-gap irregularities
- Bent shaft (similar to dynamic eccentricity) which can result in a rub between the rotor and stator, causing serious damage to stator core and windings

There are several different techniques for measuring and diagnosing of electrical machines but MCSA is considered the best since it is non-intrusive and is not affected by the type of load since its search coil is the stator windings[21].

MCSA

Motor Current Signature Analysis is a measuring technique that analyzes the current and voltage that is supplied to an electrical motor [33]. With a properly performed MCSA the following can be monitored and analyzed:

- Incoming winding health

- Stator winding health
- Rotor Health
- Air gap static and dynamic eccentricity
- Coupling health, including direct, belted and geared systems
- Load issues
- System load and efficiency
- Bearing health

There are a few key steps in performing a MCSA. Firstly it is important to understand the system and decide what part(s) of the system to analyze, after that the data need to be collected and lastly reviewed and analyzed. When analyzing the data there are three different things that need to be done

- Review a 10 second snapshot to view the operation
- Review low frequency demodulated current to detect load related issues and determine the condition of the rotor
- Review high frequency demodulated current and voltage to find other electrical or mechanical faults that do not originate from the rotor [21]

Many of the faults detected by MCSA can be detected by vibration analysis but in most cases MCSA can find the faults in an earlier stage than a vibration measurement would. With early detection of faults it is possible to avoid secondary damages created in other parts of the motor or machine [35].

3.7.4 Vibrations in motors

Many of the faults that exist in other rotating parts of machines can be present in asynchronous motors too. The rotor can suffer from misalignment, unbalance, resonance etc. just like other rotating machine parts. Since the rotation is generated by magnetic fields any problem with these will cause faults.

If the rotor is unbalanced there will be a magnetic force because of the air gap between the rotor and the stator. This will create a vibration with a frequency that is the mains frequency multiplied by 2. Normally the mains frequency is 50 Hz which means that the frequency created by an unbalanced rotor is 100 Hz. The stator can be unevenly mounted which will also create a 100 Hz frequency vibration on the feet of the stator [17, p. 66].

If the rotor is unbalanced the vibration frequency will normally be the same as the rotational speed. There is often a high frequency vibration present that is the number of rods in the winding multiplied by the rotational speed. These vibrations normally have a frequency between 600 and 1600 Hz [17, p. 67].

If one of the rods in the winding breaks there will not be any power in the rod. This will make the load on the neighboring rods heavier and this can cause the rotor to bend. The bending will create an unbalance that will cause vibrations [17, p. 68].

In addition to all these mechanical problems an asynchronous motor can also experience electrical problems. By measuring the current at the motor and doing a frequency analysis of the current, both winding problems and unbalance can be detected by comparing the results with the input values [17, p. 70].

3.8 Other measuring techniques

There are many techniques to detect and identify problems in plant equipment and machines. Most of these are either intrusive or have a too small application area that disqualify them from being used as condition monitoring devices. However, they can assist the monitoring system in detecting the root cause of the problem, examples of techniques are: acoustic emission, magnetic particle, residual stress etc. [7, p. 112].

3.8.1 Electrical testing

Electrical testing is mainly used to detect problems in and test electrical motors. The testing methods that can be used are; resistance testing, megger testing, HiPot testing, impedance testing or other techniques that might be helpful. The best application for resistance testing is to detect weak insulation or windings that are shorted together. Megger testing is used to measure high resistances and is used mostly to test the integrity of insulation. It can also detect high voltage related problems but it can not detect shorting between windings.

HiPot (High Potential) testing is used to detect problems with the integrity of insulation. It is mostly used as a quality testing tool by some equipment manufacturers. It is not recommended for field use since it does some damage to the insulation each time it is performed.

Impedance testing is used to detect shorting in coils, it is the only nonintrusive method that is able to do that [7, pp. 112-113].

3.9 Machines to monitor

When planning for installing a CBM system it is important to identify the critical machines.

The company Commtest that develops vibration measuring instruments listed critical machines in a reference manual [31] on their website in June 2006:

- Machines that are difficult, expensive, time-consuming to repair
- Machines that can become a bottleneck to production or plant operation
- Machines where damage is more frequent
- Machines whose reliability are evaluated
- Machines that are critical to human and environmental safety

Whether a machine is critical or not can be difficult to asses since the consequences are dependant on the current situation. A break down in a machine does not necessarily cause a lot of trouble. If the machine has produced enough to handle a stand still, the time can be used for cleaning and controlling components.

It can be hard to predict the costs of a break down. When planning the activities in a factory the occupancy is rarely 100 % because there needs to be time left over to take in extra orders or time for maintenance. Since there is often extra unused time in a factory it is hard to say how much money the factory loses because of a break down. The money is not lost until it is impossible to deliver the promised goods to the customer on time.

3.10 Requirements on monitoring system

The first thing that needs to be decided is what parameters to monitor; vibration, tribology, thermography, ultrasound etc. When this is done the search for a monitoring system to use can begin. It is unlikely to find a system that supports all the desired measuring techniques and a ranking of what parameters to supervise is desired.

When the parameters are ranked it is possible to choose a monitoring system but there are still a few things that need to be considered. According to Keith Mobley in the book "Plant engineer's handbook" the chosen system must have the following capabilities [8, pp. 877-879]:

- *User-friendly software and hardware*
  The users of the monitoring system must be able to understand both the

data logger and the software used in the computers. Most often it is the plant maintenance staff that will be the user and therefore the system must be fairly easy to understand since the maintenance staff rarely has an education within computer science. This is, however, not a major problem today since most people have some basic computer knowledge.

- *Automated data acquisition*
  One of the reasons to use continuous monitoring is to eliminate human errors. This is achieved by having an automated data acquisition where the choices the operator can make are limited. Having an automated data acquisition system can also reduce manpower.

- *Automated data management and trending*
  When analyzing the trends of the data collected it is important to have as much stored information as possible. If the trending is only based on the current measurements and the last few ones the results are not that reliable. But only storing the data is not enough, the data must be accessible for analyzes at all times so that correct trending data can be compiled.

- *Flexibility*
  To be able to monitor a whole plant with the same system the system needs to be flexible. The flexibility should include the possibility to choose between different monitoring techniques such as narrowband, broadband etc. It should also be able to process the signals from a variety of different transducers measuring everything from vibrations to pollution in hydraulic oil. A system that is only capable of using broadband is not of much use when it comes to tracing failing components.

- *Reliability*
  Before purchasing a new monitoring system it is important to validate that the system actually works in plants. Trusting the manufacturer of the system without having any proof that it works in field use might be a problem. To ensure that the desired system is the one to purchase you could ask for a users list to be able to talk to users and verify that you are making the right decision by learning the systems strengths and weaknesses.

- *Accuracy*
  Not all systems on the market provide the user with an accurate result from the monitoring. As in the case of the reliability of the system, the vendors are not always to be trusted. If the results are not accurate, the problem might also be that the operator has been using it incorrectly or that the software is set in an incorrect way.

- *Training and technical support*
  To understand the software and the applications of the CBM system it is important that the supplier offers a support package that offers the operators both training and technical support. Without this knowledge and services an otherwise good CBM system can become ineffective.

- *System cost*
  The price of the monitoring system should come secondary to desired features and applications. Two systems within the same price range can either offer the most basic ability to monitor vibrations or complete vibration monitoring providing process parameters, visual inspection and point-of-use thermography.

- *Operating cost*
  When purchasing a monitoring system it is easy to concentrate on only the initial cost of buying the system. The real cost is however the annual cost for retrieving and analyzing the measurements; the operating cost. The more automated the monitoring system is the lower the operating cost will be since the manpower required is lower.

Chapter 4

Statistics

4.1 Collecting statistics; QlikView

Different Tetra Pak factories, with one or both of the machines in question in their plant, were asked to provide their break down statistics, but since none of the factories provided this information the data had to be collected from QlikView. QlikView is a software designed to visualize the statistics extracted from the Tetra Pak database P2.

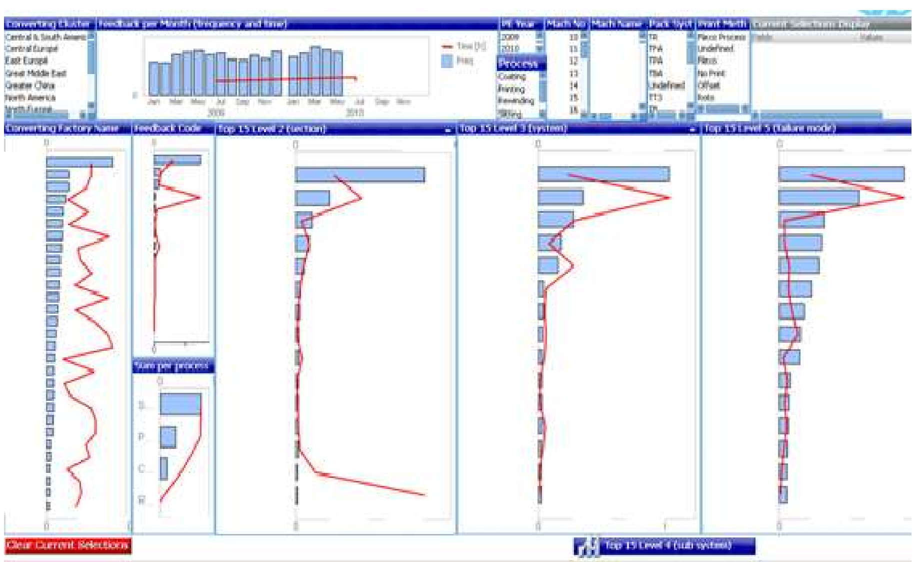

Figure 4.1: QlikView

In QlikView different categories can be chosen, depending on what may be of interest for the user. For example, the way to see the break down statistics for VT Flex 175ES in 2009 and 2010 is to choose the process "printing", choose the desired machines (VT Flex 175ES) and select the feedback code for break downs.

The first problem that arises is that not every factory has clearly specified the machine name; to be able to choose all the desired machines a list of machines in each factory has to be used as a complement. When this problem is solved QlikView will provide an overview of what section, system, subsection and failure mode that causes the most breakdowns, both in time and frequency.

When all the desired options have been selected it looks like A is the system that causes the most break downs, but the problem with the P2 system is that the factories themselves can name the different categories. When a word is spelled differently or a sentence is built up in another way, QlikView will not recognize the categories as the same. The problem starts at level 2 (section) but gets worse for every level, since the higher the level, the more influence the factories have on what to name the categories. Many of the categories are written in the language spoken in that specific factory. Many of the factories and operators also have different opinions on what a section, system, subsystem and failure mode is and what categories that belongs where.

To get a better idea of where the biggest problems are, the values can be exported to Excel, grouped together, with only one category for the same section, and then plotted again. With these selections B will turn out to be the biggest cause of break downs. When that is concluded it is possible to select all the categories in QlikView that belongs to B, the higher levels will then show what system in the B section that most often causes the break downs. The problem with categorizing is however still there and therefore it is complicated and time consuming to get all the desired data from QlikView.

Because of the problems with categorizing in QlikView no critical components were able to be identified.

Chapter 5

Focus

5.1 CBM Techniques

As mentioned earlier in this report vibration measuring is the CBM technique that is most widely used and it is also the technique focused on in this thesis. By measuring the vibrations many faults in machines can be detected. To further analyze the faults, if the vibration measuring is not enough, other CBM techniques such as ultrasonics or thermography, can be used. There can also be components that are difficult to monitor with regular vibration measuring techniques. An example can be a thrust bearing with low rotational speed. In that case an alternative to consider can be oil analysis.

5.2 Components

Since QlikView did not show what components to focus on, another approach had to be taken. In conversations with different Tetra Pak factories and the section owners for converting and printing the most critical components with respect to purchase cost, delivery time and time for repair was identified.

In the coating machine the conclusion was to monitor the drives for the extruders and in the printing machine; the drives for the printing stations. In the standard coating lines, there are a couple of extruder stations that distributes the plastic film on the paper. In the standard printing line there are several printing stations and in every printing station there are three driven rollers; an impression roller, an anilox roller and a plate roller. The plan is to monitor these components continuously with an online system and in the future this system should be extended to monitor most of the components in the converting machines.

On the following two pages there are pictures of the components in focus.

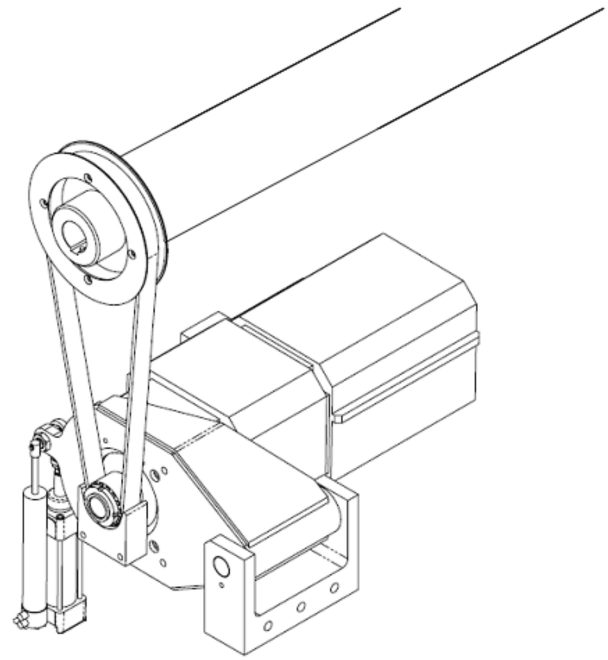

Figure 5.1: Anilox

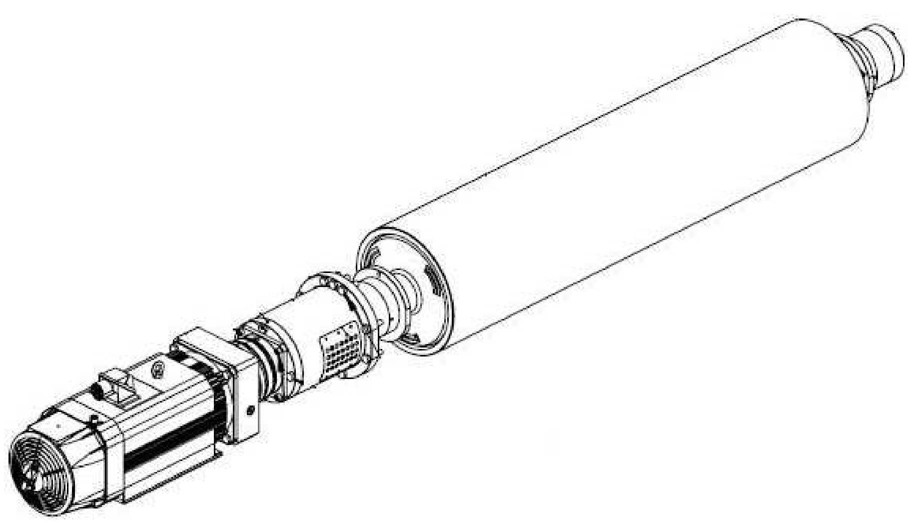

Figure 5.2: Impression roller

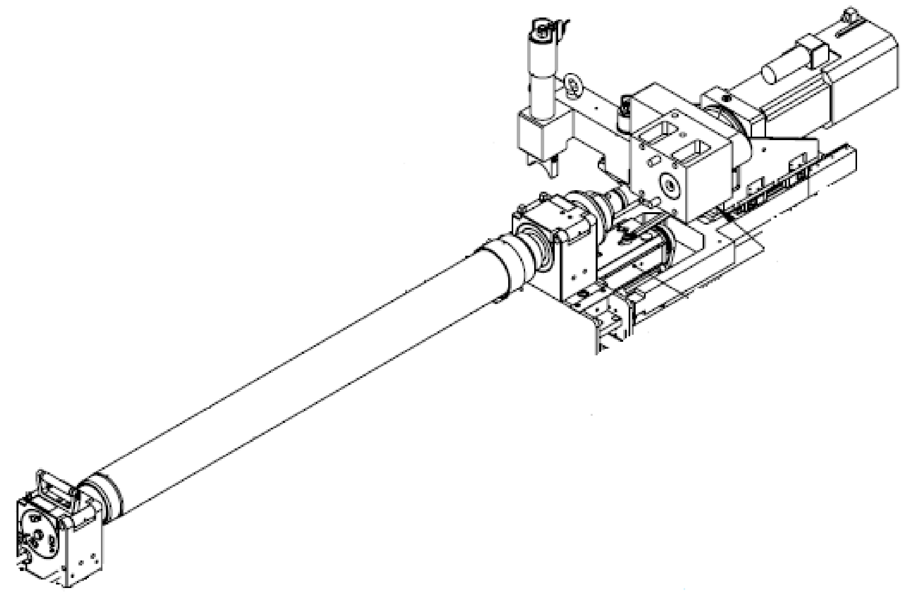

Figure 5.3: Plate cylinder

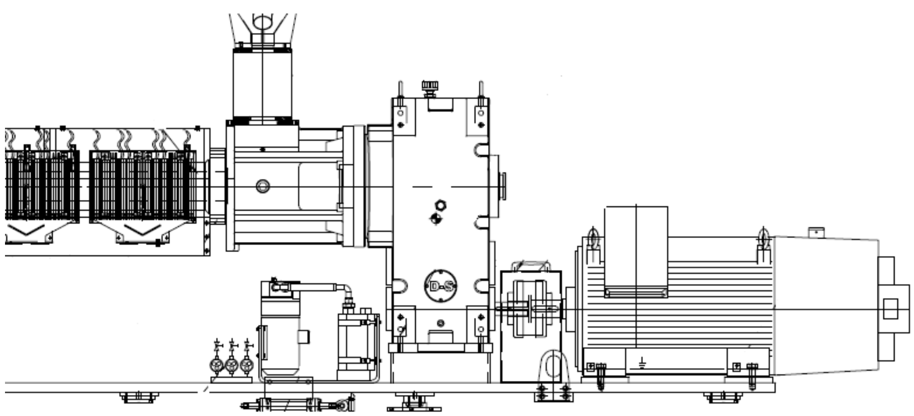

Figure 5.4: Extruder drive

Chapter 6

CBM systems on market

6.1 Systems

There are many online monitoring systems on the market and most of them are fairly similar. As mentioned earlier, vibration monitoring is the main condition monitoring technique and will therefore be the focus in the search for CBM systems. In table 6.1 many suppliers and their systems are presented with a few properties. Since the focus is on vibrations it is of great importance that the systems can handle vibration measuring techniques. The goal is to find an online system and therefore any system that is not an online system is discarded.

The number of measuring points is essential since both of the machines to be monitored are very large. In the printing machine there are about 100 rollers and in the laminator there are even more. The goal is to install a system that is expandable so that it can monitor most of the rollers and other critical parts of the machines.

Without a proper analyzing software the results from the monitoring transducers are more or less meaningless. It is in the software that the vibration signal is treated with a wide range of analyzing methods to detect hazardous vibrations by performing e.g. a FFT analysis. Most of the systems on the market have a software that can perform different analyzes but the softwares can differ in their analyzing abilities and the frequency spectra resolution. A resolution of 800 lines can detect faults but it might be too few and more lines are preferable.

Table 6.1: CBM systems on market

	Measuring techniques	**Online**	**Number of measuring points**	**Resolution (lines)**
ABB	Current, vibration	Yes	4/unit	
SKF	Vibration	Yes	32/unit	<6400
PCH-engineering	Vibration	Yes	4/unit	<800
Askalon (CSI)	Vibration	Yes	48/unit	<6400
SPM Instruments	Vibration, SPM	Yes	32/unit	<12800
Holroyd Instruments	Acoustic Emission	Yes	64/unit	
Beving (Bkvibro)	Vibration	Yes	48/unit	
Vibrationsteknik	Vibration	Yes	32/unit	<3200
DLI Engineering	Vibration	Yes	16/unit	<25600
Parker	Oil and air	Yes		
National Instrument (NI)	Vibration, sound	Yes	16/unit	
Provibtech	Vibration	Yes	48/unit	
Rockwell Automation (enwatch)	Vibration	Yes	2-6/unit	<800
VSC	Vibration etc	Yes	8/unit	
GE-energy	Vibration etc.	Yes	14/unit	<3200
Monition Ltd	Vibration etc.	Yes		
Fluke	Thermography	No		
Prüftechnik	Vibration, SPM	Yes	9/unit	<12800
ifm	Vibration	Yes		

In table 6.1 there are 19 companies presented but all of them are not suitable for the applications in this thesis. A few of the companies can be neglected since their systems can not measure vibration. Examples are Parker and Fluke that can only measure flow and do thermograhy respectively. Another reason not to choose some of the companies is that their systems are not able to handle the large amount of measuring points needed to monitor the printing press and the laminator. The empty spaces in the table mean that the information was difficult to identify.

Since most of the monitoring systems are similar and the transducers are able to measure almost the same parameters the company providing the system is not the most important factor. This thesis is based in Lund, Sweden and has mainly focused on companies situated in Sweden to facilitate the communication and demonstration. This, however, does not mean that all the systems are Swedish, some of the companies are resellers for other companies systems.

After doing this first assessment of the companies and their systems, a few of them remain and will be further evaluated after meeting technical representatives from the companies. Not all companies that seemed interesting were able to visit Tetra Pak for a meeting and it could be of value for Tetra Pak to meet them in the future to discuss their systems.

6.2 System data

To further investigate some of the companies the most important properties of the companies and their systems were identified. Since the focus is on vibration measurements the systems needed to be able to measure vibrations, any other measuring technique was considered a bonus but not necessary. Many of the companies have different methods for measuring the vibrations in bearings. The company SPM calls their technique SPM, Askalon calls theirs PeakVue etc. If the systems had any other measuring techniques like oil analysis or motor analysis these were listed.

The more measuring channels there are per unit the less number of units need to be installed in the machine. If every unit only has two channels the number of units in the machine will be very large and the wiring will be extensive. If the measuring points could be collected in fewer units the number of cables connected to the main unit would not be as many.

As mentioned earlier a system is only as good as its user and therefore it is very important that the personnel using the system and analyzing the data gets the proper training. Without training the data can not be processed in the right way and information might be lost.

To determine if the system is useful and where to put the transducers a test

Table 6.2: CBM system data

	SPM	**Askalon**	**MLT**	**SKF**	**vtab**	**EON ES**
Measuring method (vibrations, currents etc.)	Vibrations, SPM, standard signals	Vibrations, PeakVue	Vibrations, oil etc	Vibrations, oil etc.	Vibrations, standard signals, motors	Vibrations, motors
Measuring channels	32/unit	Up to 48/unit	9/unit	Up to 32/unit	Up to 32/unit	Up to 16/unit
Reseller/ Developer	SPM	Askalon/ Emerson	MLT/ Prüftechnik	SKF	vtab/ Areva	EON ES/ AzimaDLI
Training and technical support	Yes	Yes, Support contract	Yes	Yes	Yes	Yes
Cost for upgrades/updates of software	Yes/No	Yes/Yes	No/No	Yes/Yes	Yes/No	Yes (Low)
Possibility to expand system	Yes	Yes	Yes	Yes	Yes	Yes
Measuring techniques/ transducer	Vib or SPM	Vib and Peakvue	Vib and SPM	Vib	Vib, Shockfinder	Vib
Cost (SEK)	~100 000/ unit	~300 000/ unit		~115 000/unit		~100 000/ unit
Free system trial	Yes	Yes	Yes		Yes	

installation can be performed. If this gives good results buying and installing an entire system is the next step.

A monitoring system is not just installed and then instantly perfectly tuned; the system will need a few weeks or months of fine tuning before it works as it is supposed to. To get the best settings possible the user will need help from the supplying company since they are the experts and a company that has an extensive service program to help get the customer started is therefore crucial.

Software usually needs updating every few years and this can be very expensive. Sometimes software can be upgraded to contain more functions and applications that can be useful. Some companies have free updates and upgrades while others have free updates but no upgrades. Another way of handling this is that the customer can sign a support contract that among other things also contain updates of the software.

Some transducers contain only one measuring technique while others contain two or more. A specialized SPM transducer can only measure shock pulses from bearings and to measure other vibrations in the surrounding machine components a vibration transducer would have to be added.

6.2.1 SPM

SPM is a Swedish company but has locations in over 50 countries in the world. The main part of the production takes place in Sweden.

SPM recommended Tetra Pak to use their online system Intellinova which can be put together of modules, each with 32 channels. The only limitation to the number of modules in a system is network capacity.

Intellinova can receive data from many transducers measuring vibrations, shock pulses, temperature, rotational speed and any other analog signal. It is also possible to connect a thermography picture to the measuring data in the software.

The shock pulse method makes it possible to detect small cracks in bearings and condition of lubrication oil. The shock-pulse transducers should be placed at the loaded zone on the bearing's housing. SPM will help with the measuring to detect the loaded zones and recommend placement of the transducers. A transducer called SPM HD have been developed to be able to monitor bearings with very low rotational speeds.

Alarm levels can be set to take process- or other parameters like rotational speed and motor effect into consideration.

The software Condmaster Nova uses FFT diagrams to analyze the measuring data and in the software is a bearing catalogue with the ISO numbers the system needs for the analyzes.

An online measuring system from SPM will be tailor-made to fit the specific needs of Tetra Pak and costs are based on the functions and methods desired. There is a yearly cost for a service agreement since the vibration transducers has to be calibrated etc. Updates are free of charge, but there is a cost for upgrades.

6.2.2 Askalon

Askalon is the reseller of Emerson Process' monitoring system CSI6500 in Sweden. Emerson is a large international company with over 129 000 employees and is represented in all parts of the world. Askalon have approximately 40 employees.

During a meeting with Askalon they recommended Tetra Pak to use the system CSI6500. CSI6500 is an online monitoring system with 24-48 channels/unit. There is no limit on the number of units that can be used in a system.

The user of CSI6500 has the possibility to set the alarm limits and have different alarm levels for different rotational speeds. Askalon can help with the installation and set up of the system so that the transducers are placed correctly and that the alarm levels are set on a proper level.

The software used together with CSI6500 is called AMS Suite. AMS Suite can process and interpret results from a wide range of measurements; from laser alignment to thermographic pictures.

The analyzing technique PeakVue is a type of enveloping that can detect early bearing damages. The technique removes the normal vibrations, that are always present in a machine, and can thereby detect the high frequency and low strength vibrations that bearing damages create.

As mentioned earlier Askalon can help set up the system and they can also arrange education on using both the software and the system. When purchasing an online system from Askalon a service agreement is included the first year and after that a new contract has to be signed.

6.2.3 MLT

Prüftechnik is an international company represented in more than 80 countries all over the world. The reseller in Sweden is MLT (Maskin- och Laserteknik). When meeting MLT they recommended Tetra Pak to use Vibronet Signalmaster to monitor the printing press and the laminator. Vibronet Signalmaster has up to 162 measuring points per system and several systems can be used with the same software. The transducers can measure both vibrations and shock pulses in the same measuring point. Prüftechnik use current signal in their cables but many other systems use voltage signals. According to Prüftechnik the current signal can travel further without loosing strength, up to 800 meters.

The system can retrieve operational data from the control system such as rotational speed, temperature etc. and use it in the software to correctly analyze the data.

If measuring the vibrations on rolling bearings that are placed closed together one transducer might be enough. The strength of the signal can be used to trace the vibrations to the correct bearing. The shock pulse method can be used to identify the correct lubrication interval.

Prüftechnik have other monitoring techniques to offer as well. MLT suggested that Tetra Pak installs a particle counter to measure the contamination in the lubrication oil. The particle counter can be connected to the software to help analyzing the condition of the machine.

When installing a system from Prüftechnik, MLT can help with setting up the system and tune the alarm levels. They can also help setting up a test system to evaluate the results and the possibilities to install a permanent monitoring system.

There needs to be at least 30-35 transducers in the system before it becomes economically justified to install it. For this application in the printing press and the laminator that amount of transducers will be exceeded fast. MLT provides upgrades and updates of soft- and firmware free of charge. An extra cost is the cost for calibrating the transducers.

6.2.4 SKF

SKF's system for online monitoring is called IMx-S and has up to 32 channels per unit. To these channels different transducers can be connected for measuring vibrations, oil analysis, temperature measurements and other analog signals.

The software, @ptitude observer, has an expansive analyzing platform with many different options for performing different analysis. For detecting defects in bearings before they can "be seen by the human eye", enveloping is used.

@ptitude observer can be taught to distinguish different process parameters or different behavioral patterns and connect them with a specific situation. For example; if there are vibrations every time the machines are ramped up, the system can be taught that this is the normal condition.

SKF can provide the services of installing and setting up the entire system with interfaces and alarm levels, all depending on how much each factory is willing to do themselves. An option is also to let SKF take care of the analysis and send reports to Tetra Pak e.g. every week. If the factories choose to handle the condition monitoring themselves, a service contract can be signed to get support and checks of the system.

At the meeting with the SKF sales representative it was emphasized that the most important thing is how the data is analyzed and how much knowledge that is behind the diagnostics.

Tetra Pak is an important customer to SKF and SKF is represented all over the world.

6.2.5 Vibrationsteknik (vtab)

Vibrationsteknik AB was founded in the 1940s in Sweden. They are resellers for a few different companies, although only one online system. They recommended Tetra Pak to use the system called MVX from Areva that is an online monitoring system with 32 channels per unit.

The system is installed in several places all over the world e.g. in a few paper printing factories in France. The alarm limits can be set with reference to the process parameters.

The system is compatible with a module for monitoring electrical motors which can be used to complement the vibration measurements. However this module is not always the best method of detecting if something is wrong with the motor, sometimes vibrations are a better indicator.

The software used together with MVX is called XPR and is available in three different levels depending on what features are necessary to correctly monitor the machine. Tetra Pak would have to use the highest level called XPR Premium to have access to all the desired features.

The system has a method of detecting vibrations in slower rotating bearings that could be useful in the thrust bearing in the extruder of the laminator.

Installation will be performed with an hourly cost and there is an extra cost for upgrades of the software. For support, 01dB/Areva has a hotline that answers questions via email or telephone.

6.2.6 EON ES

EON ES are resellers of monitoring systems from both PCH Engineering and AzimaDLI. The systems from PCH Engineering are small and simple systems that are probably not advanced enough to be used in the applications treated in this thesis. Their systems lack a sophisticated software that can analyze the results and they leave most of the analyses to the personnel which acquires highly trained personnel.

The system from AzimaDLI is based on small units of four channels that are able to do simultaneous measurements. Four small units can then be connected to a MUX unit and a system can consist of many MUX units. The signals from the MUX units can be treated in different ways; either in a database in or near the factory or via a web portal. The function that uses the web portal does not need any software in the factory and the cost for software and updates is therefore not as high.

The transducers can use the techniques vibration, enveloping and cepstrum. Cepstrum is a way of detecting the rate of change in a spectrum by using the FFT plot in a logarithmic diagram.

The system from AzimaDLI uses a software called ExpertALERT. The software can be used to analyze signals from transducers but it can also be taught how and when to measure. It can take process parameters and decide if it is going to measure or not. This can be done via OPC which is a communication standard between different computers. Via OPC the measuring system is told when it is going to measure or what results that are normal based on the process parameters. This can be done for every part or component in the machine.

The system does not save all measurements done, only those measurements that in any way differs from the normal readings.

A simple HMI interface can be built using Microsoft Office Excel. This interface can contain the whole machine train with alarm buttons that tells if something is wrong.

The representative from EON ES recommended the usage of thermography to detect faults in the machines. By using thermography components in the machines that are not vibrating but are not functioning correctly can be detected. According to him even the simplest thermographic cameras can be used.

Chapter 7

Evaluation of CBM systems

7.1 Choosing a supplier

Tetra Pak has a policy to only deal with companies that follow Tetra Pak's code of conduct. This means that they do not want to make business with companies that e.g. use child labour, are corrupted or in any other way violates the code of conduct. These codes of conduct are important to follow when choosing a supplier and have to be followed. No violations of this policy were found in any of the companies that were researched a bit more deeply.

Another criteria that should be considered is that Tetra Pak is an international company and the system chosen should be possible to mount in Tetra Pak's converting machines all over the world. A supplier that has resellers in many parts of the world is therefore desirable.

7.2 Discussion of criteria

An evaluation of the different CBM systems was performed with the criteria stated in chapter 3.10 as starting point.

When evaluating the products, the quality and reliability are probably the most important factors, but they are factors that are difficult to asses. Each examined company provided case stories from other companies where their products have helped in saving a lot of money, but naturally they would not provide stories that proved the opposite. To be able to really review the products quality and reliability a test installation has to be made and the results have to be analyzed and compared. Suppliers that offer installation, testing and setup of the system can make sure that all transducers are correctly mounted and that they measure the right parameters at the right location. Since many of the CBM techniques are complex it might be difficult for someone that is not an expert to decide the correct choice and placement

Table 7.1: CBM system evaluation

	Weight	SPM	Askalon	MLT	SKF	vtab	EON ES
Help with installation and configuration	**5**	5	5	5	5	5	5
Provides education	**4**	5	5	5	5	5	5
Service and support	**5**	5	4	5	5	5	5
Possibility to use several CBM methods with same software (yes=4)	**3**	4	4	4	4	4	4
Alarm limits with consideration to process parameters	**4**	4	4	4	5	4	5
Additional costs	**3**	4	3	5	3	4	4
Global availability	**4**	4	4	4	5	3	4
Previous cooperation with Tetra Pak (yes=4, no=2)	**2**	2	4	4	4	4	2
Total score (Maximum 150)		**130**	**126**	**137**	**139**	**130**	**134**
Scaled price		*1*	*0.70*	*0.68*	*0.67*	*0.65*	-

of transducers. An incorrectly placed transducer can affect the results and hazardous vibrations can be undetected.

Another important factor when choosing a supplier is how important one more customer will be to that company. If the supplying company is too big in relation to the order in question, they are not as likely to provide good service and support e.g. not as dependant on keeping this customer. Here previous cooperation can also be considered, that is; if your company already is a big customer to the supplier in another area, they are more likely to, in this new area as well, provide the service and support needed. A small company will be more dependant on their customers, but a disadvantage could be that they are less likely to be globally available. Since global availability is considered important this is also graded.

In addition, the advantages and disadvantages of supplying the companies own products or being a reseller can be discussed. A company that is selling their own product probably have a deeper knowledge of their products and might even have the possibility to customize the product for the specific implementation. On the other hand, they only have one type of product to sell and might not see the broader picture.

Help with installation and configuration, education, service and support are important factors to consider since it does not matter if the CBM system is the best on the market if you can not analyze and interpret the data. The scores given in these categories are based on if the companies provide the specific services and in the category "Service and support" the service provided when doing this survey of companies were also accounted for.

The system's ability to process several CBM techniques in the same software is essential because there are several different components in the converting machines and the best monitoring results are not necessarily given by vibration measuring alone. This question is simply answered by yes or no.

In the converting machines all of the process parameters are rarely the same and therefore it is a central ability for the system to be able to set alarm limits in consideration to process parameters. The systems capability to learn what vibration values to expect at a certain load is evaluated and graded.

An additional factor that has been evaluated is the supplier's additional costs, e.g. the extra costs after the system has been installed. A high number here means low additional costs.

The environmental awareness of the companies that are not already collaboration partners should be further investigated if a new collaboration should be of interest.

7.2.1 Weight of criteria

When determining the weight of the criteria that could be evaluated, help with installation, configuration, service and support were considered to be most important. The reason for this is that the results from the measurements are meaningless without the proper knowledge. To provide education and global availability was considered to be important for the same reasons, and alarm limits connected to process parameters was considered important to be able to account for different operating conditions. If the system cannot distinguish a normal condition from a dangerous, the measurements are pointless.

Previous cooperation with Tetra Pak is an advantage in the sense that the company is already evaluated and additional costs is a factor that should be considered, but neither one of these factors should be decisive.

7.2.2 Price

The price of the system should not be the deciding factor but merely a guide. Different companies have different support contracts that have very different prices and the updates of software can also be a large cost. All the prices, except the one from SPM, are based on a suggestion of placement of transducers made by MLT. SPM:s proposal contains a lot more transducers than MLT:s. The suggestion of placement of transducers from both MLT and SPM will be presented in the next chapter.

As seen in table 7.1 the prices are almost the same for four of the companies. All the prices that were given have been divided with the highest price, the one from SPM, to get a scaled view. Since the prices are almost the same this should not be a deciding factor when choosing a system. The prices given are all approximate which means that the real prices can differ from the ones presented here and the ranking could change. EON-ES did not give a price before this report was finished and is therefore not part of this evaluation.

7.3 Results: CBM system evaluation

In table 7.1 it can be seen that the companies that were further investigated all received similar scores and any one of the six companies could be a potential cooperation partner. The suppliers are also very even in their prices. What should be pointed out is that the price SPM gave is based on a vaster distribution of transducers and therefore the prices cannot be compared directly.

Chapter 8

Results

8.1 Placement of transducers

Three companies were asked to give their suggestions of where to put the transducers. Both MLT and SPM gave their suggestions which are presented below. Askalon referred to Tetra Pak's mechanic that measures vibration with the motivation that he probably knows where the transducers are needed.

8.1.1 Suggestion by MLT

As mentioned earlier in the report the focus areas for a first installation is the extruder drives together with the drives in the print stations.

In the print units the suggestion was to put one transducer on every bearing on the three rollers, in total six transducers in every print station on roller bearings. Every roller has a drive with a motor and a gear. That unit could be monitored by two transducers. This makes the total amount of transducers in a print unit 12.

In the laminator it is the extruder drives that are the main focus of the initial installation. The suggestion from the MLT sales representative was to put two transducers on the motor, four on the gear box and possibly one on the thrust bearing. A suggestion was to put an oil analyzer on the thrust bearing, this would however be more expensive. In total there would be seven transducers on each extruder.

The four transducers on the gear box should be placed as follows: one on the input shaft on the drive side, one on the input shaft non-drive side and one on each side of the output shaft.

Figures 8.1-8.4 show schematically how the transducers can be placed.

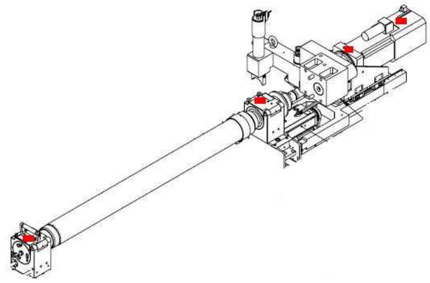

Figure 8.1: Placement plate deck

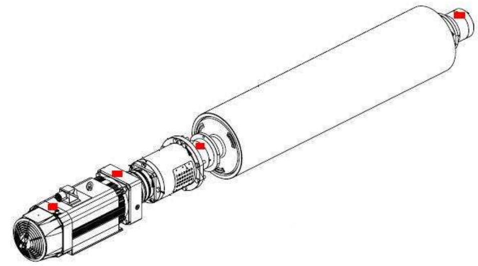

Figure 8.2: Placement impression roller

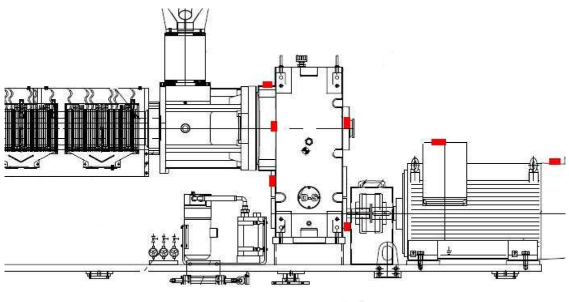

Figure 8.3: Placement extruder

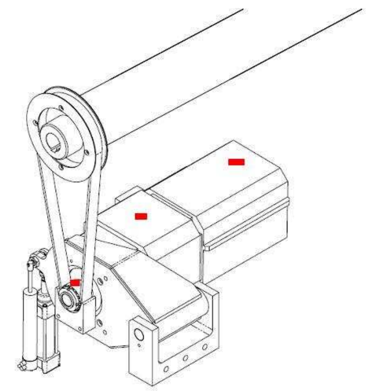

Figure 8.4: Placement anilox

8.1.2 Suggestion by SPM

SPM gave recommendations of placement of transducers based on drawings of the components. They have one kind of transducer for measuring with the shock pulse method, which they recommended to use on all bearings. They also have a vibration measuring transducer, which they recommended to use for detecting misalignment and defects in gearwheels.

In one extruder drive the suggestion was to put two regular SPM transducers, seven transducers called SPM HD and two or three vibration measuring transducers.

On the motor the idea was to put one vibration transducer axially on the non-drive side to pick up misalignment in the motor and the coupling. The plan was also to put one SPM transducer on either side of the motor.

Two vibration transducers can be placed on the gear, one axial and one radial. Moreover, to monitor the bearings in the gear, one SPM HD transducer was suggested to be placed on each bearing housing i.e. four SPM HD transducers total in the gear box.

To monitor the thrust bearing, the suggestion was to put a SPM HD transducer as close to the bearing as possible, on the bearing housing, in the loaded zone.

In the print units on the printing machine the suggestion was as follows: On the anilox; place two SPM transducers on the motor; one on the drive side and one on the non-drive side. The bearings in the gearbox need four SPM transducers and the gears can be monitored with one accelerometer that also can catch any problem with the belt. The anilox roller needs one SPM transducer on each side to monitor the bearings. In total the anilox roller needs eight SPM transducers and one accelerometer.

The impression roller has a similar structure and therefore the placement of the transducers is similar. The roller needs one SPM transducer on each side on the bearings, the gearbox needs one accelerometer acting axially and one that measures the vibrations from the cogs. Because this gearbox is smaller than the one on the anilox roller it does not need to have SPM transducers to monitor the bearings. The coupling housing could possibly need one accelerometer acting axially. The transducers acting axially on the gearbox and the coupling housing could be used to measure alignment. The total amount of transducers are three accelerometers and two SPM transducers.

The cliché roller has a large gearbox and therefore need several transducers to be fully monitored; two accelerometers axially and one to monitor the cogs. The motor needs one SPM on each side and the roller bearings needs one SPM each. In total the cliché roller need three accelerometers and four SPM transducers.

The suggestion can be seen in figure 8.5-8.8

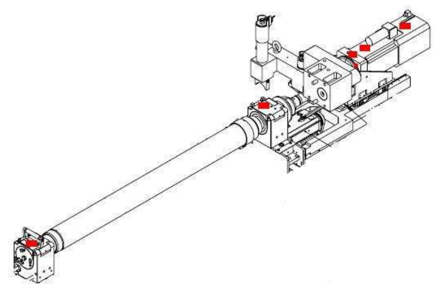

Figure 8.5: Placement plate deck

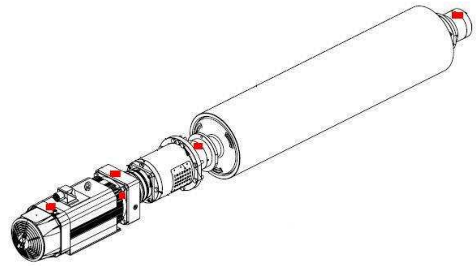

Figure 8.6: Placement impression roller

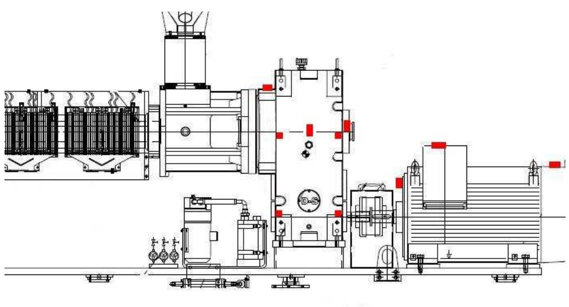

Figure 8.7: Placement extruder

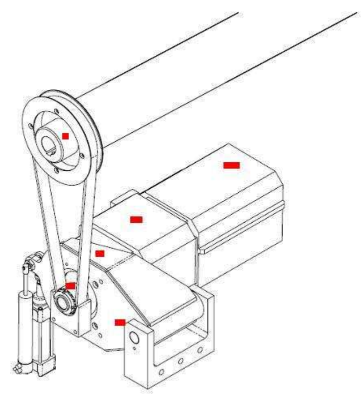

Figure 8.8: Placement anilox

Chapter 9

Discussion

9.1 Problem areas

9.1.1 Cliché roller

The cliché roller is the roller with the print offset on it. The size of the roller is varying depending on the type of package material it is printing. Not only the diameter of the roller changes; the pattern on the roller is different for every different print pattern. Both of these factors make it hard to measure the vibrations on the roller since the shape and value of the vibrations will change with every different size and pattern of the roller.

To be able to use vibration measurement as a CBM method anyway there are different ways to go. The easiest is to set up the system to only measure the vibrations for one size of roller; this would make the system not fully online since it would only measure the vibrations when triggered. Another solution is to teach the system how to see the difference between normal vibrations and dangerous vibrations. This could be done by looking at the trending level and asses the trend instead of setting of an alarm every time the vibration level is too high. The diameter and pattern of the cliché roller can then be registered in the system and next time the same diameter and pattern is used the alarm will not go off if the vibrations are higher than the alarm level.

9.1.2 Moving of rollers

The rollers in the print station are taken out of their positions at a regular basis. The cliché roller is changed often, a few times every hour, due to the different print patterns and the anilox roller is taken out and cleaned.

The moving of the rollers might be a problem when placing the transducers. The transducers are placed on the rollers bearing housings and they might be in the way when moving the rollers.

To get the correct placement of the transducers, and still be able to take out the rollers, the technicians at Tetra Pak and the supplying company should be consulted.

9.1.3 Thrust bearing

In the extruders in the laminator there are thrust bearings placed after the gearboxes. These thrust bearings have a low rotational speed compared to the other rotating parts of the machines. The low speed makes it hard to detect any vibrations and vibration measuring might not be the best CBM method to use. The condition of the thrust bearing can be detected e.g. by doing oil analysis on the return lubrication oil. There are continuous oil analyzers that can be connected to the lubrication oil cleaning system that can report the status of the oil to the same software used to supervise the condition of the other parts of the machine. This can be helpful in monitoring the whole machine train as one system. Another way is to use the shock pulse method, which will detect defects earlier than vibration measurements. The downside with the shock pulse transducers is that they have to be mounted very close to the bearing housing, which can be hard to do, depending on the construction of the extruder station. A third option is to use thermography to identify components that have a higher temperature than the surrounding components. The higher temperature indicates damages.

9.1.4 Moving of extruders

The extruders are placed on large wagons that are moving the extruders in and out of the laminator depending on if they are being used or not. When moving the extruder the transducers will be moved too and to be able to do this the cables need to be placed in a way that let this happen. The technicians at Tetra Pak or at the supplying company should be able to suggest a placement of transducers and cables that makes this possible.

9.2 Choosing a supplier

To Tetra Pak it is not mainly the cost of the system that will decide what system to buy. There are many criteria that are more important, such as; training of personnel, support, global availability etc.

Since Tetra Pak has factories all over the world a company that can provide global service is important if the same system is to be used in all factories. The situation where all factories have a monitoring system is however likely far in the future. Even so, a small local company with only a few employees is less likely to be able to provide the support and service that Tetra Pak requires.

Educating the personnel to be able to correctly analyze the data collected by the monitoring system is very important, as mentioned before. All companies that were more deeply investigated were providing the service of having training courses for the personnel. A monitoring system, however, is not something that is completely mastered in a few days course and long term support is necessary.

As mentioned earlier the possibility to perform a test installation should be utilized since that could help in choosing a good system. It could also simplify the placement of the transducers since the transducers in the test installation would not be screwed into place but rather glued to the surface or be fastened with a magnet. The transducer could then be moved until the location of the maximum vibration signal is identified. The test installation could help the future analysts in understanding the possibilities of a monitoring system and it could also help them to learn the system.

9.3 Placement of transducers

MLT is a previous partner to Tetra Pak and the sales representative had knowledge about Tetra Pak's machines. His recommendation of where to put the transducers was, because of that, considered to be valid and trusted. This suggestion contains less transducers than the suggestion made by SPM and if less transducers could be used to monitor the same area with the same results this would be good. Less transducers means less cables which is desirable since the this would facilitate the maintenance and moving of the rollers and extruder wagons.

9.4 Outsourcing of analyses

The intention was to find an online system for vibration monitoring and educate Tetra Pak personnel in analyzing the results and managing and tuning the software. When monitoring entire machine trains, however, this will probably require establishment of one or two full time positions in condition monitoring analyses.

A better option can be to outsource the analyses to companies with analysis centers with experts within the area. There are two ways this can be done; either the analyzing service can be obtained or merely the results presented in a report each week or month.

9.5 Visualization in HMI

HMI stands for Human Machine Interface and is the technique used in the industrial world for interaction between humans and machines. The interaction can consist of starting or stopping a machine or it can be used to monitor the machine condition.

When using the HMI to monitor the machine condition there is a risk that the machine operator ignores the multiple alarms that can be the result when monitoring a whole machine train. The HMI is currently used as a communication link between the operator and the machine where the operator can set or monitor the operational parameters for the machine.

Because the HMI is the communication link between the operator and the machine there is a risk with having the CBM alarms in the HMI because the result might be that the operator disregards the alarms so that the machine does not have to be stopped. If this is done frequently the damage that the alarm is warning about might be worsened. Another risk with having the alarms in the HMI is that the operator might not know what to do about the alarms and therefore disregards them.

One way to minimize the risk of ignored alarms is that a mechanic has the responsibility to monitor the condition of the machine. The alarms could come to his/her computer and then it is up to him/her to decide what to do about the alarms. Sometimes the alarms certainly can be ignored but it has to be by qualified personnel. The software used in a CBM system often has a possibility to set several different alarm levels. This can possibly be utilized so that the lower alarm levels are sent to the mechanic that can plan the maintenance but the highest level of alarms are sent to the operator that can decide if the machine can keep running or if it has to be stopped. By doing this the amount of alarms to the operator are minimized but the machine is still operating safely.

For optimal visualization in the HMI the alarm should be connected to the part in the machine that set of the alarm. Lets say that one of the bearings in the printing unit has elevated vibration levels; the alarm should be visualized by a picture showing the right printing unit with e.g. an arrow pointing at the vibrating bearing. The operator can then decide what to do, call on a mechanic or shut down the machine if the vibrations are too dangerous.

Chapter 10

Conclusions

Several companies have the technology to monitor the converting lines but a recommendation of a system and supplier could not be made since no test installations were made and therefore the quality of different measurements and analyses could not be assessed.

Below are factors that should be considered when choosing a system/supplier.

- A test installation of the suppliers system should be made and evaluated.
- The options of support should be a more important factor than costs in further investigations of suppliers.
- Economical analyses should be done to decide if the data analyses should be outsourced or if Tetra Pak should do them internally.
- The supplier should offer education in vibration analyses.
- Global companies should be given an advantage.
- The placement of transducers should follow the suggestion made by MLT after confirmation by a test installation.
- Not all alarms should go to the operators but instead be managed by the maintenance staff.

Chapter 11

Future recommendations

11.1 Improving QlikView

As mentioned, QlikView is far from a perfect instrument for collecting statistics. To be able to draw any conclusions from the statistics collected and compiled from all the factories it is important to know that all the statistics are included but today this is not the case. For QlikView to become a better instrument for conveying statistics it would be a good idea to decrease the options for the factories to write their own explanation of what happened. Every machine should be divided into sections, possibly with a drawing to explain what section is named what, so that the operators are not able to give the same sections multiple names. This method could be applied to the higher levels of the machines too, a drawing with the right names clearly stated so that the room for errors decreases. The only level where the operator should be able to describe the problem with his/her words should be the highest level. If this was implemented it would be a lot easier to collect statistics from QlikView and draw conclusions from the statistics. The decrease in options for the operator to describe what has happened could possibly decrease the time they have to spend documenting the problem since they do not have to think about what to write when they are only allowed to choose from a list of pre-defined options. This could also decrease the many different languages that are now present in QlikView and this would be a great improvement since translating and sorting in Microsoft Excel is a time consuming task.

11.2 Outsourcing of analyses

Tetra Pak should investigate the possibilities to outsource the analyses of monitoring data. The competence within the CBM supplying companies is great and to build up the same competence internally at Tetra Pak would be both expensive and take a lot of time. By utilizing the suppliers expertise this can be avoided. An economical analysis of what would be most beneficial should therefore be performed.

11.3 Expansion of CBM system

In this report a suggestion is made on what components to monitor and where to put the transducers in an initial installation. In the next step the chill rollers and the nip rollers in the laminator should be monitored. The expansion of the system should eventually include the whole machine trains.

In the unwind and rewind there are a lot of moving parts and many possible causes for break downs and therefore these parts should be monitored. This expansion could be done at the same time as the nip and chill rollers are included.

Bibliography

Tetra Pak internal

[1] Tetra Pak, *Tetra Pak – development in brief*, 2008–06 [Online]. http://www.tetrapak.com/Document%20Bank/About_tetrapak/9704 en.pdf. [2010-06-30]

[2] Tetra Pak, *Tetra Pak Print Specification*, Internal document.

[3] Tetra Pak, *Lamination Converting Process*, Internal document.

E-books

[4] V. Ferrari and P. Gatti, *Applied Structural and Mechanical Vibrations: Theory, Methods and Measuring Instrumentation.* Taylor & Francis e-Library 2003.

[5] W. Forsthoffer, *Forsthoffer's rotating equipment handbook.* Vol.3. Elsevier, 2005.

[6] W. Forsthoffer, *Forsthoffer's rotating equipment handbook.* Vol.5. Elsevier, 2005.

[7] R. K. Mobley, *An Introduction to Predictive Maintenance.* Elsevier, 2002.

[8] R. K. Mobley, "Predictive maintenance" in *Plant engineer's handbook.* R. K. Mobley Ed. Elsevier, 2001, pp. 50/867–50/888.

[9] C.W. da Silva, *Vibration Monitoring, Testing and Instrumentation.* CRC Press, 2007.

[10] G. W. Younkin, *Industrial Servo Control Systems Fundamentals And Applications.* CRC Press, 2002.

Printed books

[11] M. Alaküla, J. Johansson, G. Lindstedt and B. Simonsson. *Grundläggande elektroteknik* Lund, KFS AB, 2006.

[12] E. Befring, *Forskningsmetodik och statistik*, ed. 1:9. Malmö: Studentlitteratur, 2008.

[13] R. E. Browne, A.K.M. De Silva, K. P. Ramachandran and D. K. Harrison, "Machine Health Monitoring Using Coast Down Time Analysis–An experimental investigation" in *Condition Monitoring and Diagnostic Engineering Management*. U. Kumar, A. Parida and R. B. K. N. Rao. Luleå, 2006.

[14] M. Höst, B. Regnell and P. Runeson, *Att genomföra examensarbete*, ed. 1:3. Malmö: Studentlitteratur, 2010.

[15] O. Jansson, *Hydraulik Underhåll*. Förlagstryckeriet Vitterleken 2007.

[16] G. Lindholm, *Vibrationer i maskiner, del 4 av 10 Vibrationskontroll*. Stockholm, Mentor Communications AB, 1995.

[17] G. Lindholm, *Vibrationer i maskiner, del 6 av 10 Vibrationsorsaker*. Stockholm, Mentor Communications AB, 1996.

[18] O. Olsson and K–E. Rydberg, *Kompendium i hydraulik*. Institutionen för konstruktions– och produktionsteknik, Linköpings universitet, 1993.

[19] L. Vedmar and B. Jacobson, *Tribologi*. Maskinelement Lunds Tekniska Högskola 2008.

[20] L. Vedmar, *Transmissioner*. Maskinelement Lunds Tekniska Högskola 2007.

Articles

[21] N. Mehala and R. Dahiva, "Motor Current Signature Analysis and its Applications in Induction Motor Fault Diagnosis", *INTERNATIONAL JOURNAL OF SYSTEMS APPLICATIONS, ENGINEERING & DEVELOPMENT*, vol. 2, nr. 2, 2007. www.universitypress.org.uk/journals/saed/saed-5.pdf [2010-10-01]

Electronic sources

[22] *Creative Education Foundation*, www.creativeeducationfoundation.org [2010-07-02]

[23] Presentation made by Emerson at the University of Texas at Arlington, http://arri.uta.edu/acs/cbm/CSIemerson.ppt [2010-08-18]

[24] *Linetic AB*, www.linetic.se/eddycurrent.html [2010-07-13]

[25] *Linetic AB*, www.linetic.se/vibration.html [2010-07-13]

[26] *E.ON ES*, www.eon-es.se/templates/Eon2TextPage.aspx?id=47986&eps language=SV [2010-07-11]

[27] *Omega Engineering*, http://www.omega.com/techref/iredtempmeasur.html [2010-07-11]

[28] R. Lovicz and R. Dalley, *Wear Particle Analysis - A Predictive Maintenance Tool*, www.reliabilityweb.com/art05/wear_particle-analysis.htm [2010-08-09]

[29] *Spectrometric Oil Analysis–An Untapped Resource for Condition Monitoring*, www.journal.au.edu/au_techno/2008/oct08/12(2)_Article06.pdf [2010-08-09]

[30] *Utbildningsstyrelsen*, www.edu.fi/laboratorieanalyser/analysmetoder/2_kromatografiska_metoder) [2010-08-09]

[31] *Commtest*, Beginners guide to machine vibration, http://commtest.com/media/downloads/beginners_guide_to_machine _vibration.pdf, [2010-09-15]

[32] *SPM Instruments*, www.spminstrument.se/methods/spm/ [2010-09-22]

[33] *Motor Current Signature Analysis and Interpretation*, www.motordiagnostics.com/papers/motor%20current%20signature%20 analysis%20and%20interpretation.pdf [2010-09-22]

[34] *Seattle Robotics Society*, www.seattlerobotics.org/guide/servos.html [2010-09-29]

[35] W. T. Thomson, R. J. Gilmore, Motor Current Signature Analysis To Detect Faults In Induction Motor Drives – Fundamental, data interpretation, and industral case histories. http://mopsaco.com/Articles/Motor%20current%20signature%20ana lysis.pdf [2010-10-01]

[36] V. Wowk, *A brief tutorial on machine vibration.* www.machinedyn.com/revised/tutorial.pdf [2010-10-04]

[37] *Gears Manufacturer*, www.gears-manufacturers.com/planetary-gears.html [2010-10-04]

List of figure references

[A] www.pneac.org/images/2rollsyswdocbla.jpg

[B] Tetra Pak Internal (Lamination)

[C] Tetra Pak internal (Lamination)

[D] http://arri.uta.edu/acs/cbm/CSIemerson.ppt?bcsi_scan_B6EBA8E9 BD81F969=0&bcsi_scan_filename=CSIemerson.ppt# 507,21,Slide 21

[E] http://arri.uta.edu/acs/cbm/CSIemerson.ppt?bcsi_scan_B6EBA8E9 BD81F969=0&bcsi_scan_filename=CSIemerson.ppt# 507,21,Slide 21

[F] www.ndt-inspection.com/nutek/technology.htm

[G] V. Ferrari and P. Gatti, *Applied Structural and Mechanical Vibrations: Theory, Methods and Measuring Instrumentation.* Taylor & Francis e-Library 2003. p.3

[H] www.efunda.com/designstandards/sensors/lvdt/images/lvdt_Ratiometric _Wiring.gif

[I] www.pc-control.co.uk/images/accel1.jpg

[J] V. Ferrari and P. Gatti, *Applied Structural and Mechanical Vibrations: Theory, Methods and Measuring Instrumentation.* Taylor & Francis e-Library 2003. p.26

[K] http://knol.google.com/k/-/-/2ufdlj2yc019u/ubyyel/piezoresistive-accelerometer.jpg

[L] www.pcb.com/Accelerometers/Sensing_Technologies.asp

[M] www.sensorland.com/HowPage019.html

[N] http://en.wikipedia.org/wiki/File:Electrical_fault.jpg

[O] www.journal.au.edu/au_techno/2008/oct08/12(2)_Article06.pdf Spectrometric Oil Analysis–An Untapped Resource for Condition Monitoring

[P] www.journal.au.edu/au_techno/2008/oct08/12(2)_Article06.pdf Spectrometric Oil Analysis–An Untapped Resource for Condition Monitoring

[Q] Tetra Pak internal (Printing)

[R] www.vibrationschool.com/mans/SpecInter/Gse01.jpg

[A1] www.zakgear.com/Split_Gear.html

Personal communication

Tetra Pak

Johan Brunlid, Converting Specification/Section Owner
Mats Göransson, Converting Module/Section Owner
Stefan B Johansson, Mechanic, Maintenance Lamination/Slitting
Lars G Nilsson, Mechanic, Maintenance Lamination/Slitting
Bengt J Olsson, Mechanic, Maintenance Prepress/Printing
Gabriela Pinto, Manager, Strategic Planning Packaging Material
Johann Steiner, Manager, Mechanical Engineer
Fredrik Swernfeldt, Mechanic, Maintenance Prepress/Printing
Anders Tullberg, Maintenance Manager

Other

Lars Vedmar, Lector LTH, Lecture in Transmissions – dynamics, March 15th and 23rd 2010
Sales representative from MLT
Sales representative from SKF
Sales representative from Askalon
Sales representative from SPM
Sales representative from EON-ES

Appendix A

Thesaurus

Nip roller
A roller that holds the paper at the right tension. It is located near the chill roller.

Chill roller
A chill roller is a roller in the laminator that has water flowing through it to cool it down. The chill roller's task is to chill the laminated paper.

Unwinder and Rewinder
The part of the machine where the paper is unwinded from the roll into the machine or rewinded from the machine to the roll.

P2 system
A system where all paper waste in the machines is reported. All break downs and short stops in the machines are reported but also any other reason that the machines might stand still.

ES (Electrical shaft)
In VT Flex 175 ES the abbreviation ES stands for Electrical Shaft. This means that all the printing units have their own electrical drive. In the older machines, called Mechanical Shaft, there were one drive that were distributed to all the print units via a cardan shaft.

Fully radiometric
The higher the radiometric resolution the more realistic an image is presented. In thermography this means that a surface can be presented with temperatures in all points, or at least in all pixels of the screen.

FFT (Fast Fourier Transform)
Is explained in chapter 3.2.2. A mathematical algorithm to transform time based results to frequency based results.

Contact angle

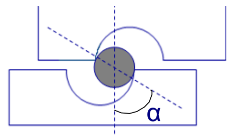

Figure A.1: Contact angle α

In the figure is a bearing seen from the side. The contact angle is α.

Dynamic range
A ratio between the smallest and largest possible measuring value.

Frequency response
The spectrum response of a system on an input signal.

Mass loading effect
If the structural mass is very small the mass of the transducer can affect the measuring result.

Planetary gear
A planetary gear consists of a central sun gear with a fixed axis and one or more planet gears mounted on a moving axis (carrier), that move around the sun gear. Outside of the planet gears there is an outer ring gear [20].

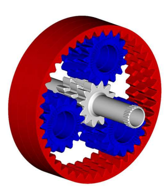

Figure A.2: Planetary gear
[A1]

Planetary gears are often used in automatic transmissions together with brake bands and clutches to give different gear ratios depending on which gears that are moving [37].

Appendix B

Converting machines

VT Flex 175 ES

The printing technique used in VT Flex 175 ES is flexographic printing. Flexographic printing, or flexo, is a technique that uses relief image plates of polymer material. The plates are placed on the plate cylinder that puts the ink on the paper.

The printing process starts with the unwinding of the paper into the machine. The roll is spliced onto the previous roll so that it can follow the path in the machine. In the unwinding section there is a section called the festoon which can move in or out to either stretch the paper or provide extra paper when it is needed during the splice.

The first station in the machine is web cleaning. When this is done the paper is transported through the printing units where the ink pattern is printed onto the paper. The paper goes through all the print stations but depending on how many colours the pattern has, the paper is either printed or just transported through the print station. After every one of the print stations the paper goes through a drying hood that dries the ink so that it will not smear when the next colour is printed.

When all the printing is done the paper is creased so that it can easily be folded into packages later in the process. This unit is not considered in this thesis.

After the paper is printed it is first inspected so that the print is within the quality range and then the paper is rewound onto a roll and transported to the laminator.

The unit that gives the paper the right tension through the machine is the pull and brake unit. It consists of several rollers that together can either release some tension or give the paper more tension by moving slightly back or forth. For an overview of the printing machine see figure B.3.

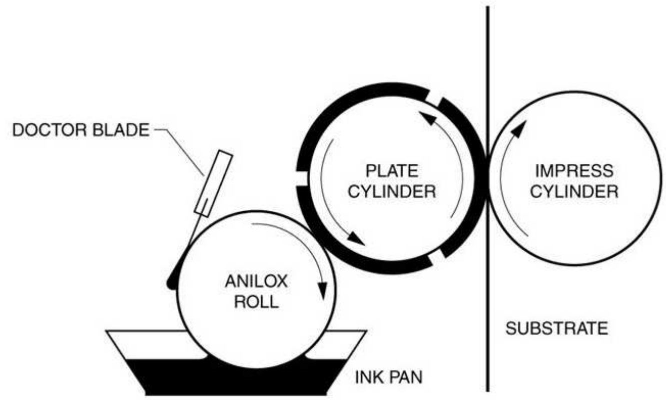

Figure B.1: Flexographic printing
[A]

The printing technique is, as mentioned, flexographic printing. This technique is based on mirrored, relief patterns of the print on polymer plates. The plates are attached to the plate cylinder with double-sided adhesive tape.

An anilox roller, with laser engraved pattern of small cells, is the ink carrier between the ink pan and the plate cylinder. The anilox roller rotates with one side in the ink pan, a doctor blade then scrapes the excessive ink off of the roller before it is in contact with the plate cylinder. The ink in the small cells on the anilox roller is then transferred to the relief pattern on the plate cylinder [2].

VT Lam 650/6 WRM

The purpose of the laminator is to apply layers of plastic film and, if needed, aluminum foil to the already printed paper, see figure B.2.

The roll of printed paper is put on the unwinder, spliced onto the last part of the previous roll in the coating machine and then it follows the path through the machine.

The paper then goes through the festoon and the pull and brake. These sections are the same in both the printing machine and the laminator.

Surface treatment is done by flame treating the paper to enhance the adhesion between the paper board and the polymer. Another way to get the same effect is corona treating.

The laminator stations apply film and aluminum foil onto the board. The aluminum foil is unwinded from a roll and the polymer film is extruded onto the board. In the extruder the polymer pellets are melted down with the help of a screw.

In the laminator stations there are two important rolls; the nip roller and the chill roller that together makes sure that there is an even nip pressure. The chill roller also cools down the polymer, gives the surface the right structure and gloss and drives the web at the right speed and tension.

Before the laminated paper board is rewound, a laser inspects the inside surface[3]. A picture of the machine can be seen in figur B.4.

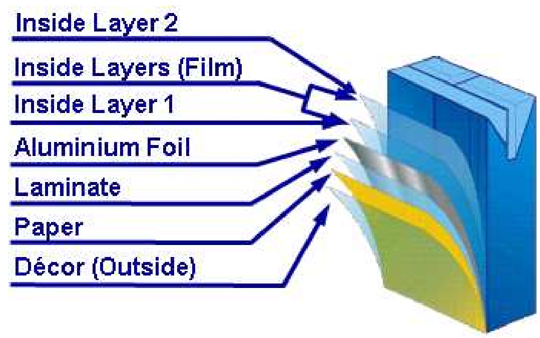

Figure B.2: Layering
[B]

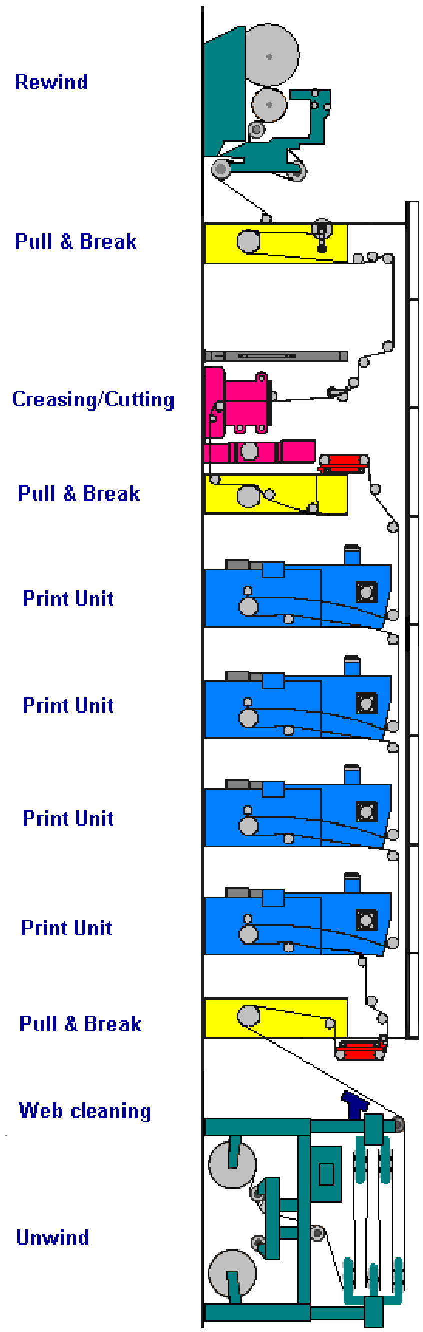

Figure B.3: VT Flex 175
[Q]

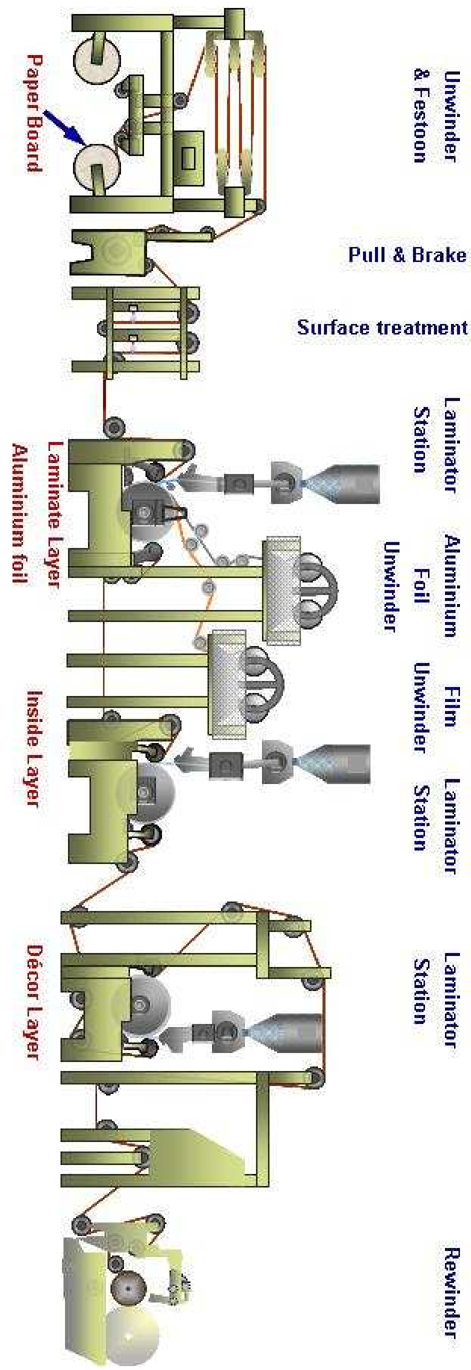

Figure B.4: VT Lam 650
[C]

Appendix C

Current status in Tetra Pak factories

To learn the current status of monitoring methods in Tetra Pak's factories all over the world an email survey was sent to the maintenance managers and factory managers. Far from all the factories answered the email and therefore there is no information about several of the factories. Where possible, personal interviews were performed or further email contact was established.

Factory A

Factory A has a well developed monitoring and maintenance program with a number of different monitoring techniques. For vibration measuring Factory A uses a portable instrument from Rockwell automation called Enpac 2500. The instrument can measure vibration, speed, do bearing analysis etc. The two channels makes it possible to do balancing in two planes.

By using thermography Factory A have detected faults such as misalignment in pump motors. The instrument used to detect this was a Fluke Ti30 IR camera that is a fully radiometric camera. When uploading the pictures to the computer there is a feature in the computer software that can create routes to help with monitoring the machine.

By using ultrasonics Factory A can discover leaks, cavitation and bearing faults. They use an instrument called SDT 170.

Oil analysis is performed by an external company.

Factory B

In Factory B there is a handheld vibration instrument that is used to measure vibrations approximately every 30 days in the machines. The measurements are performed by an external company that uses an instrument from CSi. Not all the desired measuring points are measured today since many of them are hard to reach when the machine is running because of the protection shields surrounding the machines.

Thermograpy is done every 120 days.

Factory C

Factory C is doing vibration measurements and thermography every 3 months with portable instruments. For vibrations they have the portable instrument DLI DCA-31B from Azima DLI that can measure acceleration, velocity and displacement. The instrument can be used to check bearings and there are several optional accessories that can measure pressure, oil status etc.

The thermographic camera is a Fluke Ti25, similar to the one used in Factory A.

Factory D

In Factory D there is an outsourcing company that does manual vibration measurements on motors every 3 months and oil analysis on oil tanks larger than 30 l and gearbox tanks larger than 50 l every year. The vibration instrument is Enpac 1200, very similar to the instrument used in Factory A. An instrument from SPM called Bearing Checker is using the shock pulse method to check the status of the bearings.

Thermography is used to monitor the condition of high and low power stations and electrical cabinets in the machines. The camera is a ThermaCam P60 from the company FLIR. The thermography is performed by the maintenance staff in the factory.

The factory has thermocouples in some of the motors in the machine to detect if the temperature becomes too high. If the signal from those measurements is too high the machine is automatically stopped.

Factory E

SKF is performing vibration analysis and thermography at Factory E with portable instruments. The vibrations are measured every month and the thermography is done twice every year.

Analysis on the oil is performed every month and the results are combined with the vibration measurements to get an overview of the status in the machines.

Factory F

As many of the other factories, Factory F uses vibration measuring, thermography and oil analysis to check the status of the machines. The vibration measuring instrument and the thermography camera are portable instruments. The instrument measuring the vibrations is using a technique called Acoustic Emission by the manufacturer Holroyd Instruments. The technique is similar to ultrasonics.

Factory G

Vibration

At the Tetra Pak factory G there is one person working with vibration measurements on rolls, bearings, motors and fans. The equipment he uses is a hand held instrument; CSi 2120 that uses an accelerometer with a piezomaterial to translate vibrations into electric signals. The CSi 2120 is also a tachometer and this allows measuring of rotational speeds.

At this moment there are no fixed sensors in the printing machine but there are 14 in the laminator. Sensors from old machines have been saved and are planned to be used in the printing machine at locations that are hard to reach.

Measurements on critical parts, i.e. the parts in the printing units, are made four times per year and measurements on other components two times per year. This makes it possible to discover around 12 low performing bearings every year.

One measurement takes between 5 and 30 seconds to finish.

Instrument
The CSi 2120 uses two techniques; demodulation and PeakVue. Demodulation isolates specific fault frequencies and Peak Vue can identify stresses that come from cracking in gear teeth, wear etc. It is possible to use the CSi 2120 with rotational speed as low as 10 rpm. Balancing and alignment are other applications where CSi 2120 can be used.

Oil analysis

Oil analysis is a part of the maintenance program at Factory G today. The analyses are performed by a mechanic in average two times every year on all the oil systems. The factory has an oil cleaning system that is always running on one of their machines but is transferred between different sections and machines when it has cleaned the oil. The result of the cleaning is that the oil almost never is dirty and it rarely causes break downs. The intervals for cleaning the oil are based on experience. If the oil is more contaminated than the acceptance level it is refilled with clean oil equal to 10-20 % of the total volume. The cleaning machine together with the filters in the oil systems removes all particles that are larger than 0.8 μm.

The lubrication oil does not have the same high requirements of cleanness as the hydraulic oil and it does not need to be cleaned and refilled as often.

There are sensors in the hydraulic oil systems that monitors the temperature to verify that it is in the acceptable range.

Thermography

Thermography is only performed at the electrical cabinets today. Factory G hires an external company to come and do the measurements required. This is something that the factory wants to take over and have the personnel to do themselves. When performing a thermografic measurement on an electrical cabinet it is possible to detect loose contacts.

The maintenance manager is interested in knowing the possibilities of measuring the temperature to determine the condition of the machine. Both thermography and temperature probes could possibly be used to detect faulty bearings and other machine parts.

Factory H

Factory H is doing vibration measuring, thermography and oil analysis. The measuring is done by either internal Tetra Pak staff or an external supplier. The vibration measurements are done with an instrument from SKF by the internal staff. The same staff performs the thermography but the oil analysis is performed by an external company.

There were comments from this factory that it is difficult to do measurements on the machines while they are running and the factory is therefore looking into permanently mounting transducers where needed.

Factory I

In Factory I the internal staff is performing the vibration measurements and the thermography every month. They use a vibration instrument from SKF and an IR camera from Fluke. The thermography is done on electrical cabinets.

On big oil reservoirs they are taking oil samples that Shell is analyzing for them.