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ABSTRACT
Maintenance is not only for solving technical problems as many may consider. It as a matter of fact is for solving production related problems, such as technical, environmental, etc. cost-effectively. This is why the technical part of maintenance, e.g. focusing on developing condition monitoring (CM) technology is not always sufficient alone to achieve a cost-effective maintenance policy. Without the maintenance management part responsible of identifying problem areas, data acquisition, management and analysis, decision-making procedures, planning and performing maintenance tasks at high quality and cost-effectively, the output of using any CM system cannot be guaranteed to be beneficial. In this paper, Condition monitoring and condition-based maintenance is introduced and discussed with respect to the differences between them. Also, the procedures required for establishing and running a condition/vibration-based maintenance is introduced, motivated and discussed.

KEYWORDS: Establishing condition-based maintenance, Condition Monitoring, Vibration-based maintenance

INTRODUCTION
Condition-based maintenance (CBM) is according to the British standard BS 3811:1993 carried out according to the need indicated by condition monitoring (CM) system. In other words, maintenance action should not be planned and performed until there are clear and obvious evidences of damage initiation, damage development or what is called a potential/imminent failure. Therefore, CBM is the management toolbox required for planning data acquisition and analysis, and utilisation of the information has been collected from relevant CM techniques to plan, time schedule and perform maintenance actions effectively. Using a CM system, the machine condition is assessed by the current and historical measurements of one or more of relevant CM parameters, such as temperature, vibration, Shock Pulse Measurement (SPM), pressure and acoustic emission.

In general, vast majority of the mechanical failures and UPBFR (unplanned–but-before-failure replacements) are preceded by some detectable indications of changes in the condition of components/equipment. UPBFR are usually performed at unplanned but before failure stoppages to prevent the occurrence of failures. Note this situation arises because of a sudden increment in the measured variable(s), e.g. the vibration level, due to undetected damage at an early stage or insufficient knowledge and experience of the maintenance staff using the CM system.
From everyday experience, temperature and SPM have many limitations, which restrict their use in mechanical fault diagnosis and in the prediction of the time to the next maintenance action. Vibration is always preferred in CM applications for rotating and reciprocating machines, Al-Najjar (1997) and the references cited there. Sound analysis is not widely used because the signal of vibration is more easily interpreted than the signal of sound. The implementation of vibration monitoring programs provides possibilities for acquiring early indications about changes in the state of a component/equipment. These indications could be of great importance in even detecting deviations in the product quality early and before they show on quality control charts, Al-Najjar (2001).

Vibration spectral analysis provides a basis for identification of damage causes, damage initiation, damage developing mechanisms and failure modes for most types of faults in rotating and reciprocating machines. By an efficient vibration-based maintenance (VBM) policy, which means utilising the information provided by vibration monitoring system and software program for planning and performing maintenance actions, the machine can run until just before failure as defined by the monitored parameter reaching a pre-determined unacceptable value, Al-Najjar (1997). But, limitation and deficiencies in data coverage and quality reduce the effectiveness and accuracy of the vibration-based maintenance see for example Al-Najjar (1997, 1998, 2000 and 2007) and the references cited there.

CM AND CBM
Condition monitoring (CM) technology as it well known is a source of information that can be utilised for mapping the condition of a component/equipment. CBM is not just a tool for gathering measurements from CM systems, or a tool for diagnosis and prognosis the condition of a component/equipment that is exposed to a deterioration process. It is a strategy that includes several policies, such as vibration-based or SPM-based maintenance policy, Al-Najjar (1997), which describes how the following activities should be performed;

1. Data acquisition of a certain CM parameter or set of parameters
2. Analysis and interpretation
3. Data management
4. Fault detection
5. Diagnosis and prognosis
6. Decision-making
7. Planning and performing maintenance actions required on the condition of the component/equipment under consideration.

CBM policies can be realised by utilising different CM parameters or sets of parameters, because in some cases as it well-known, one CM parameter cannot be enough for reflecting changing in the state of a component properly. CBM policy can practically designed by considering for example;

1. Selection of a CM parameter, or a set of parameters
2. Identifying where to measure
3. Identifying the frequency of measurements
4. Tools required for analysis, interpretation, diagnosis and prognosis of the signals/measurement
5. Principles for setting warning and action/replacement levels
6. Knowledge and experience required by maintenance personnel

In this paper, we use CBM to indicate the utilisation of condition-based data for performing all the activities mentioned above and not just predicting the time to action or diagnosing what has occurred as are usually called Predictive or Diagnostic maintenance.

CBM usually applies the deterministic approach for analysing, interpreting data, diagnosis or prognosis and decision-making. In many cases, even the prediction of the time to action or the level of the CM parameter value during the close future is done by using extrapolation technique, see for example Al-Najjar (1997, 2000) and references cited there. Applying only the deterministic approach can be counted as one of the shortages in CBM applications, because the real life is hardly to be expressed by only a deterministic approach. Probabilistic modelling of the residual time or the assessment of the probability of failure of a component by converting CM measurements to the time axis without considering analysis, diagnosis and prognosis, e.g. of the vibration measurements and following up damage development, cannot highlight the whole picture of the condition of the component/equipment.

As a simple role; the more relevant and accurate data concerning the deterioration process under consideration demands the less need for probabilistic modelling. Keeping in mind, the latter cannot be eliminated as long as the deterioration process is a stochastic process. Therefore, for enhancing the certainty of data and decision-making process, we believe that the probabilistic modelling, such as probability of failure, residual time, etc. is complementary to the deterministic approach when the CM parameter value is increased significantly. In other words, it is not to replace the deterministic approach by a probabilistic modelling through feeding CM data in statistical model.

The distance between identifying and selecting relevant CM parameters, i.e. those information parameters that can be used to describe the component/equipment condition until a cost-effective decision is made using CBM, rather long and complicated, see for example Al-Najjar (1996 and 1997) and Moore and Starr (2006).

In order to achieve a cost-effective maintenance decision, the data used are necessary to be relevant, of high quality and reasonable coverage. These data cannot be gathered without selecting the most informative CM parameters integrated with relevant data from production process for highlighting maintenance technical impact. But, it will not be possible without technical analysis for identifying machine problem areas and components, because we restore machine after failure by replacing or repairing components. In other words, significant components, damage initiation process, damage developing mechanisms and their failure modes should be identified clearly. They help to identify the CM parameters that can be used for monitoring deterioration phenomenon and finally selecting the most informative. All these steps are important for establishing and run a cost-effective CBM policy.

The problem addressed in this paper is; how should we establish and run cost-effective condition –based maintenance?

**PROCEDURES TO ESTABLISH CBM**

Developing procedures for establishing and running CBM policy is very important because there is no basic on that are published yet according to the survey done by the author. In order to achieve an efficient CBM it should be established properly and according to reasonable references. In this section we will try to establish the references
required to establish and run cost-effective condition-based maintenance policy. The concept has been used for developing this model is simply described in Fig.1. There no way to achieve cost-effective improvements without reliable identification, localisation and analysis of problem areas and root-causes including the lateral interaction. The latter cannot be approached without better mapping of the production and maintenance situation which is impossible to be done effectively without high quality and better coverage measurements of relevant CM parameters.

| High quality data and of reasonable coverage collected from relevant CM | Reliable mapping of component/equipment condition at need | Identification, localisation and analysis of problem areas and root-causes | Decision-making, task planning & performing | Result analysis & cost-effective improvement |

![Fig.1. Concept used to develop the procedures for establishing CBM](image)

1. Identification of the problem areas, i.e. machines, sub-systems and components, in the production process using company’s databases and experiences. From everyday experience, it is necessary to identify and localise problem areas in a production process, line or station before start thinking about effective improvements and preparing reliable tools required for realising these improvements. What is necessary for identifying and localising problem areas is technical analysis of the equipment in question, which includes among others;
   - Analysis of failures, UPBFR, planned and condition-based replacements
   - Production data and statistical tools to determine;
     - Types of stoppages and their localisations
     - Occurrence times, frequency, consequences and durations of the stoppages
     - Production amount and its time schedule
     - Additional relevant production data, such as production and quality rate, etc.
   - Additional production disturbance factors
2. Technical justification of the possibility of solving some or vast majority of these problems through using CBM policy, e.g. applying VBM policy. Based on the available experience and knowledge it is, in the most cases, possible to technically recognise whether the suggested CM parameter(s) or system(s) is/are relevant for detecting the changes in the condition concerning the component(s)/equipment considered in 1 above. For example, vas majority of rolling element bearing damage and potential failures can be detected by using vibration spectrum analysis. The same thing can be said about shaft, gearbox and pumps problems, see for example Collacott (1977 and 1979). This technical justification can be done based on;
   - High precision or intensive invested capital machines demand more stable condition and less defective items due to the high losses of each failure or producing a defective item.
   - Previous experience and applications’ results of the same or similar problems from other machines or companies.
3. Identification of the significant components in the problem areas identified in 1 above by using:
   o Technical analysis of the machines in question. Previous technical analysis of that machines in addition to the databases have been used for that purposes can be utilised to ease identification of the significant components. Significant components are those whose failures are either costly or dangerous.
   o Companies databases and personnel experience of the company’s problem areas, type of failures and disturbances are helpful for more accurate identification of significant components, modules and equipment and failure root-causes, or
   o Applying failure mode, effect and criticality analysis (FMECA) in addition to fault tree analysis (FTA). The first is necessary for identifying significant components while the second is a complementary tool needed for analysing failures, identification of the failure causes and understanding the deterioration process which is necessary for step 4 below.

4. Identification of damage initiation and development by using backward analysis;
   o Failure modes
   o Damage developing mechanisms
   o Damage initiation
   When the deterioration process is described according to step 3 above, it will be possible to identify causes of damage initiation, its developing mechanisms and failure modes. Also, the probable deterioration rate can be recognised, which is crucial for planning maintenance action accurately to avoid failures. All these should be done for only the significant components.

5. Identifying all relevant and suitable CM parameters and systems for each significant component using;
   o The available experience at company concerning the component/equipment under consideration. In other words, the company’s experience in monitoring technical problems are important for identifying relevant CM parameters, because applying similar or equivalent CM systems reduces the cost incurred by implementing and running new system
   o International standard, if there is such, that can be used for allocating CM systems for different technical problems and needs
   o In collaboration with experts; the expert can be useful for helping the company based on their experience in similar or equivalent machines and components.

6. Selecting the most informative CM parameters and systems. When a list of all relevant CM parameters and systems are suggested to be applicable to the case component/equipment it would be beneficial to use a particular criterion for selecting a most suitable CM parameter and system. In this paper, we suggest using the mount of the relevant information can be delivered by every CM parameter and system as a criterion for selection given that this information is all used for detecting the deviation in the component condition and take the required action when it is needed. The selection of the most informative CM parameter/system can be done through using:
   o Special models, e.g. model for selecting the most informative CM parameters, Al-Najjar (1997)
Experience from previous applications. Based on previous experience for similar component/equipment can be utilised for selecting the most informative CM parameter/system

- Manufacturer’s recommendation that is usually based on wide application experience and theoretical considerations
- Expert help that is usually based on wider practical experience from similar or equivalent components/equipment in different working environments

7. Better understanding of the deterioration processes as achieved in 3 above in addition to the experience gained when selecting the most informative CM parameters and systems enable us to determine the measuring policy of the CM parameters. In this paper, the measuring policy is determined when the following tasks are planned properly:

- Where to measure? Selecting the measuring points on the equipment to be as close as possible to the place where the deterioration is happening
- How often? The more measurements the higher cost but the more information and vice versa. Therefore, the benefit of the information gathered should justify the cost incurred

- How many measurements at each measuring opportunity and averaging? Deterioration process is a stochastic process and so that the CM measurement is. It is necessary to accurately decide the number of the measurements required for achieving a measurement representing the condition of the component/equipment. Averaging the values of the measurements during each measuring opportunity is a way to reduce, e.g. the randomness in the vibration signals

- Selecting number of the resolution lines, e.g. in vibration monitoring; the number of resolution lines may have in many cases big influence on the accuracy of interpretation especially when several fault frequencies are very adjacent to each other. From industrial experience, in order to avoid ambiguities it is beneficial, e.g. to pay more for higher number of resolution lines at vibration spectrum analysis. This is because the higher number of resolution lines the longer time needed for picking up vibration measurements.

- Noise level and noise-to-signal ration; the noise level should be as low as possible compared to the vibration signal for securing high accuracy in the interpretation of the vibration spectrum.

- Measuring method (periodic or continuous). In many cases the periodic measurements, i.e. once a month or a week is sufficient for following relevant changes in the condition of the component/equipment especially when the component/equipment is rather new or when the deterioration process has no rapid and catastrophic changes, such as the case when monitoring normal bearing wear or wear due to shortage of lubricant. The more frequent measurements the more information and the better situation of capturing changing in the condition of the component, Sherwin and Al-Najjar (1999). Continuous monitoring is not continuous in the absolute sense, because it is impossible according to the available technology used for picking up, e.g. vibration measurements. For example, measuring vibration, it always demands a period of time, e.g. seconds, for picking up the vibration signal and to repeat it several time according to the averaging number has the system been set up for.
Measuring system and software program; the measuring system consists of technician for data gathering and/or analysis, measuring instrument /analyser, transducers and in many cases software for deeper analysis of the picked up signal. The software assists signal analysis, interpretation, diagnosis and prognosis. Sometimes it can be used for predicting the time to action.

How to do measurements and select relevant transducers and connections? The quality of the data collected by using CM systems can be decided directly by the type of the transducer for picking up the signals. For example, low speed machines can hardly be monitored by accelerometer but transducer for measuring vibration or displacement is more appropriate.

Way of mounting the transducer on the measuring point; the quality of data picked up from the transducer can once more be influenced by the way of picking up the signal. For example, stable and rigid mounting of the transducer can secure continuous, stable and steady transmission of high quality data, and vice versa.

8. Data gathering route; it is important to be build in a way that making data gathering costs as low as possible through reducing man-hour required for data gathering without increasing the risk of failure. Building the data gathering route can be done with respect to;

- Measuring policy, see 7 above
- Machines layout; based on the machines layout, the rout should be build as short, simple and clear as possible

9. Determining warning and action levels; the warning and action/replacement levels are important to be set properly. Alarm levels are considered three; a level when every thing is going well before damage is initiated, warning level, i.e. when damage is under development and replacement level that the machine should not exceed and for performing maintenance action. To describe the importance of having these alert levels, for example if we consider an ideal case when these levels are set to 100% accurate on all relevant vibration frequencies in a vibration spectrum. These alarms levels can serve as a small intelligent expert system. By its assistant, it would be possible, e.g. to identify the cause behind high vibration, degree of severity and consequently know what to do. Using vibration signal analysis, the alarm setting can be done using overall vibration level, i.e. the total energy in the vibration signal, which is convenient for shaft problems, such as imbalance, bending and misalignment. The alarm setting can also be done for all significant fault vibration frequencies in a vibration spectrum. Further, alarm setting can be done dynamic, i.e. to allow it changes with respect to the changes in the speed and load, or static irrespective of machine speed and load, Al-Najjar (1998). For proper setting of these alarm levels we need to consider the following;

- The available knowledge and experience concerning alarm setting on identical, equivalent or similar components/equipment.
- Knowledge and experience concerning the deterioration process under consideration
- Past data and statistical tools relevant for alarm setting
- National and international experience and standard, Al-Najjar (1998)

10. Data analysis; the analysis of the CM measurements, such as vibration, acoustic emission and shock pulse measurements (SPM), should be analysed and interpreted
carefully, which cannot be done effectively without reliable understanding of the deterioration process in question, its development and the relation between the physical changes in the component condition and the changes in the signal. Thus, the following are considered very essential for data analysis;

- Analysis of the vibration levels of the fault frequencies using past and current data and different tools, such as, division of the values of the vibration levels to find the rate of changes, subtraction of them to assess the absolute amount of change if it is significant or not. Many other way of comparison can be done on these spectrums. The major objective of that is to highlight the nature and amount of the change in the condition of the component in a way is understandable to the user, because analysis can be done in different ways with respect to different objectives and perspectives.
- Diagnosis; it means detecting if there is any change in the component condition, describing the relation between changes in the component condition and the symptom observed in the CM system. For example, interpretation of the vibration spectrum to describe and anticipate the damage detected and its level of severity and development.
- Prognosis; based on the diagnosis done above, if the damage could be confirmed and its development mechanisms were possible to identify, it will be possible to take one more step to anticipate (prognosis) what would be happen if the deterioration has been detected will proceed. We should keep in min that these two tasks (diagnosis and prognosis) are usually done using engineering/deterministic approach. This is why analyst with technical background and experience in the problem area is crucial.

11. Result presentation, which can be done by using;

- Tables whose contents have different colours for distinguishing significant changes in the values of CM parameters of interest easier. In these tables the results of the above analysis and comparisons can be presented.
- Figures and trends; graphical figures ease the tracking of changes in the values of CM parameters
- Virtual reality, which is illustrative for describing the deterioration process and enhance the personnel understanding.

12. Determination (on the basis of the CM parameters’ levels) of when the maintenance actions should be ordered. Management of the CM data is very important to achieve a cost-effective CBM. Therefore, the level for replacement that has been set for the component condition is necessary to be used to trigger the work-order needed for performing the maintenance task required. At that point of time the procedure for doing what? By whom? How? Where? Man-hour? etc. are necessary to be clearly stated.

13. When the damage and its development is identified and localized in 10 above; what are needed, see below, for performing the maintenance task can then be determined and prepared:

- Spare parts required
- Tools and consumable material for performing the maintenance task
- The expertise (technicians) required
- Work plan describing when/who to start and when/who to finish, see 12 above
14. Determining the organization of CBM/VBM through considering
   o Anticipated number of problems that can be detected
   o Man-hour required for gathering data
   o Man-hour for detection, analysis, diagnosis, pognosis and reporting
   o Man-hour for repair
   o Man-hour for the overhead (supporting) function, such as administration and administration machinery, e.g. PC, printers, copy machine, scanner, etc. and offices and their operating expenses
   o Man-hour for planning maintenance actions
   o Miscellaneous

15. Monitor and assess the technical impact of CBM that is based on monitoring and following up the performance of the maintenance policy. This is to detect any deviation in the policy performance for avoiding consequences as soon as possible and before its impact becomes intolerable financially. To do that it is necessary to consider the following:
   o Production data; production amount, product quality, production rate, production cost per item, ton, etc.
   o Process operating reliability; production process reliability in fulfilling production schedules and the impact of disturbances on that
   o Maintenance reliability; maintenance ability to stabilise the continuity of production through reducing all types of disturbances and stoppages that influence production amount, production rate, product quality and production cost

16. In 15 above, the data required for effective mapping of maintenance processes are provided. The impact of maintenance performance influences directly the production characteristics, such as amount, rate, quality and cost. Therefore, monitoring maintenance performance demands always special indicators for;
   o Reporting the technical information, such as those characterising a production process
   o Following up maintenance performance measure for fast mapping, analysis and cost-effective decision-making
   o Identifying the technical role of maintenance on the production process and its economic impact on the strategic level.

CONCLUSIONS
In order to achieve a cost-effective CBM policy, it is necessary to utilise the relevant information provided by condition monitoring (CM) technology properly and effectively. Without maintenance management tools for identifying problem areas, data acquisition, management and analysis, decision-making procedures, planning and performing maintenance tasks at high quality and cost-effectively, the output of using any CM system cannot be guaranteed to be beneficial. Also, the confusion between CBM and CM technology should be eliminated when a cost-effective maintenance wanted to be established and run effectively. Further, applying the procedures for establishing CBM will with high probability ensure a reliable integration between maintenance management tools and CM technology.

References
British Standard, Glossary of Terms used in terotechnology, BS 3811:1993.


