

Integrating Vibration, Motor Current, and Wear Particle Analysis with Machine Operating State for On-line Machinery Prognostics/Diagnostics Systems (MPROS)

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Abstract

Integration of system process information with expert system vibration analysis to improve the accuracy of rotating machinery fault detection in on-line condition monitoring systems is the main focus of this paper. An overview of the condition based maintenance system MPROS (Machinery Prognostics/Diagnostics System) being developed for the US Navy is presented. Details are provided regarding several currently operating prototype systems installed on both shipboard and land based air conditioning plants. Finally a case study is presented which utilizes data from a prototype system to examine several of the relationships between air conditioning compressor vibration signatures and system process parameters. Understanding and utilizing these relationships will enable accurate diagnostics and provide the in-depth data that is needed to support prognostics.

Introduction

There are many systems available today that provide on-line or continuous monitoring of rotating plant machinery for Condition Based Maintenance (CBM). These systems range from relatively simple vibration switches which can provide alarm and machine shutdown information, to very sophisticated multi-channel monitoring systems which provide spectral processing, feature extraction, and expert data analysis to identify specific fault conditions and assess fault severity.

It has been found that current on-line CBM systems do not effectively utilize process information when evaluating machine condition from vibration, oil or motor current data. Many systems accept basic process information such as a signal from a PLC (Programmable Logic Controller) which indicates the machine is operating in a predefined state, usually at full system load. But what happens when the machine being monitored only occasionally is operated at full load, or it is subject to a wide range of operating states that have a dramatic impact on the vibration and motor current signatures of the machine? Periodic and trend analysis of the machine under these conditions usually results in a false diagnosis of a fault condition or in an inaccurate severity assessment for an existing fault. A primary goal of the MPROS project is to accurately evaluate machine condition, identify fault severities, and predict machine remaining life under a broad range of machine operating states. It is believed that this can be accomplished by identifying the relationships that exist between a machine's process and the vibration and motor current signatures of the machine. This information can then be integrated into the machine fault models during fault identification and for adjustment of a fault severity assessment.

A system was designed to accomplish this goal and several initial prototypes were installed which provide real data from which machine fault models are being developed and new fault models can be tested.

The prototype system discussed in this paper is part of the MPROS program of which an overview is provided in the next section.

MPROS Overview

MPROS, which stands for Machinery Prognostics/Diagnostics System is a Condition Based Maintenance (CBM) system which is being developed for the US Office of Naval Research (ONR) for use on US Navy ships by Honeywell Corporation in partnership with DLI Engineering. This system consists of MEMS (Micro Electro-Mechanical Systems) and conventional sensors located on the machinery, local intelligent signal processing devices called Data Concentrators (DCs), and a centrally located subsystem named a PDME for Prognostics, Diagnostics, Monitoring Engine. MPROS augments vibration analysis by collecting data continuously from vibration and other sensors, including temperature, pressure, current, voltage, and so on. These data streams are integrated as necessary in the DCs to provide data fusion. A second level of integration (knowledge fusion) occurs in the PDME. At this level, outputs of different diagnostic and prognostic reasoning mechanisms (algorithms) are fused to yield the best possible analysis.

A block diagram of the MPROS system is shown in Figure 1 and the algorithms and hardware required to support this system will be briefly discussed. A more detailed description of the MPROS architecture is provided by Reference 1 (Hadden et al., 1996).

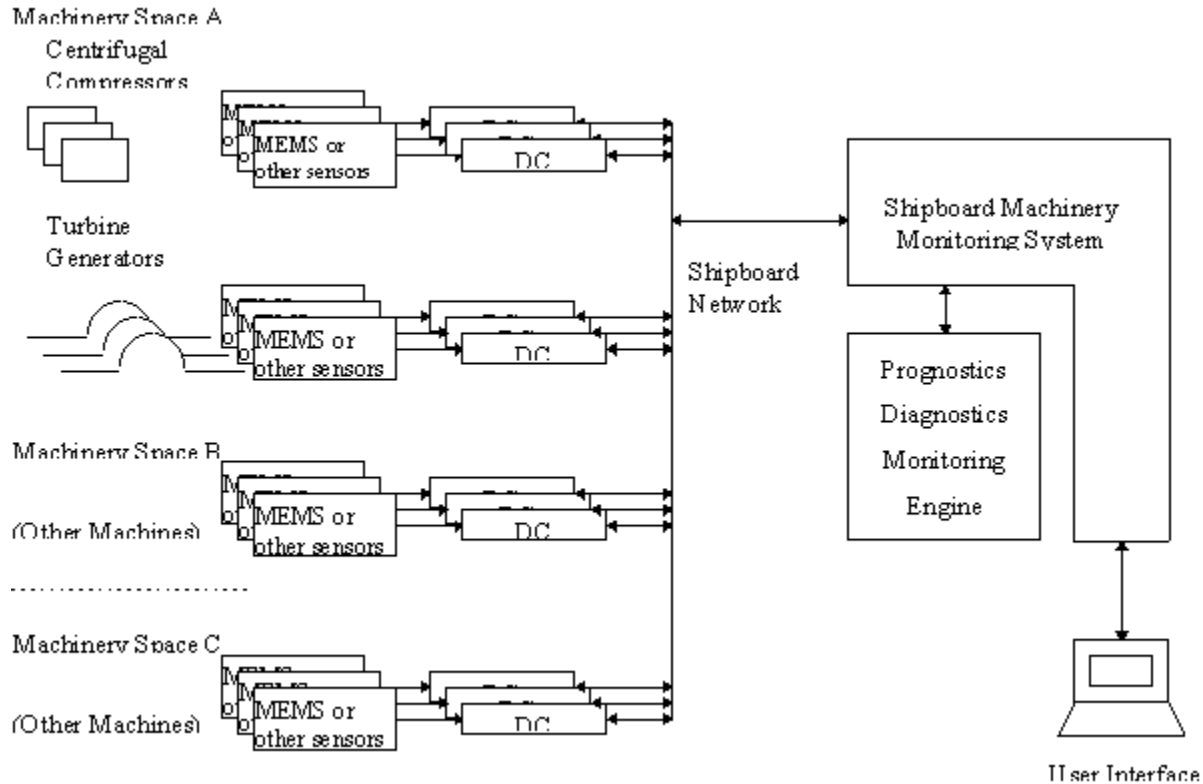


Figure 1 - MPROS System Architecture (Hadden et al., 1996)

Sensors

Sensors are selected to maximize the prognostic/diagnostic results for a machine. A mix of existing off-the-shelf sensors and standard signal processing techniques is used along with the development of new sensors and advanced processing techniques. This retains proven technology while allowing the development of more advanced sensors such as MEMS and advanced processing techniques such as wavelet analysis to be integrated into the system.

Data Concentrators

Data Concentrators (DCs) are installed on or near the machinery. They provide the link between raw sensor data and the PDME through a data acquisition, processing and analysis system. Data analysis by a DC includes State-Based Feature Recognition and neural network software for local diagnostics and prognostics, signal processing (e.g., wavelets and Fast Fourier Transforms (FFTs)), and data reduction. Analysis results and raw data are provided to the PDME and are also available locally for immediate alarm notification. If the connection between the DC and the PDME is severed the DC will continue to function and provide local reporting of machinery status. Individual DCs are configured with the setup information and processing algorithms required to analyze the particular machine that it is connected to. This can be accomplished locally or from the network connection to the PDME.

PDME Architecture

The Prognostic/Diagnostic/Monitoring Engine (PDME) is a group of software modules that run in cooperation with the Shipboard Machinery Monitoring System (SMMS). The PDME collects data through the SMMS network from the DCs and other shipboard systems, applies prognostic and diagnostic algorithms, and provides analysis, failure warnings, and machinery condition assessments to the SMMS. Figure 2 indicates the various analysis modules contained within the PDME as well as the Object-Oriented Ship Model (OOSM) which is used to represent the ship's machinery components and the significant relationships between them.

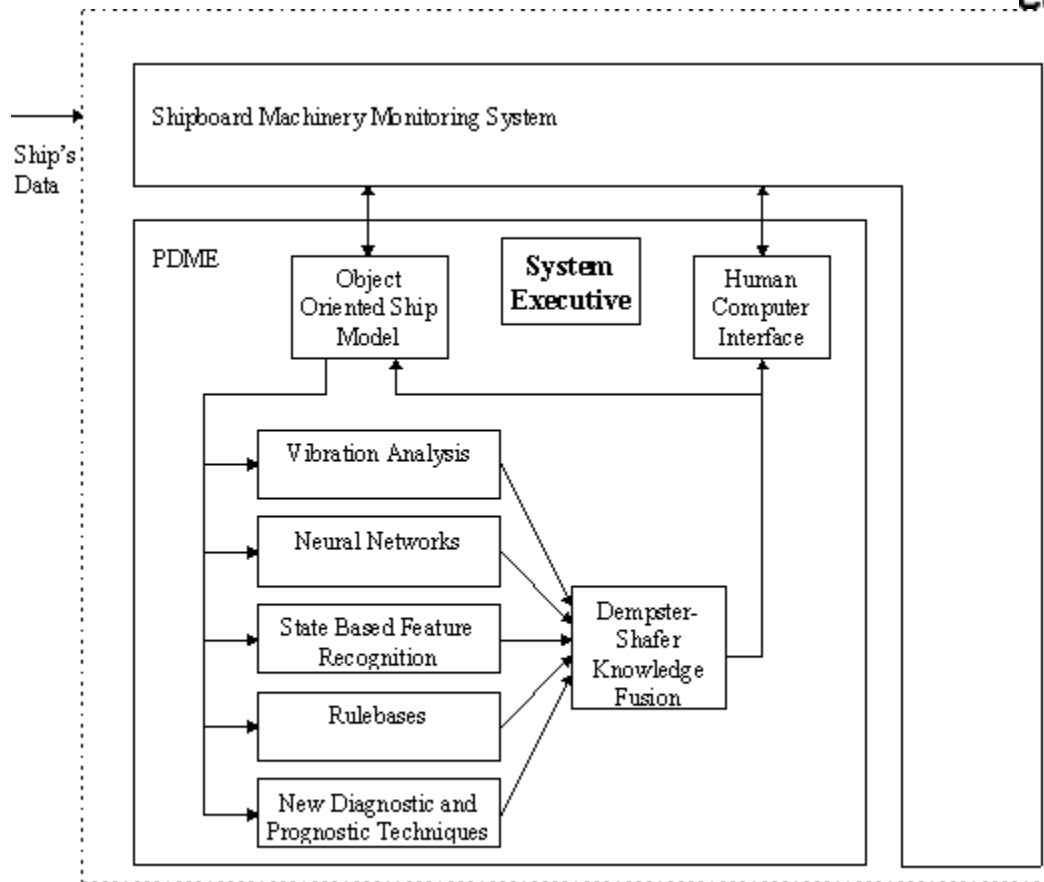


Figure 2 - PDME Block Diagram (Hadden et al., 1996)

Machinery Fault Model Development

Machinery fault models are based both on theoretical and empirical investigation. Theoretical models are derived from mathematical system models and lead to useful and accurate broad fault data definitions. For example, the theoretical effect of misalignment across a mechanical coupling can be modeled accurately knowing the stiffness of the coupling, the shafting, bearings, housings, and foundation.

Additionally, changes in vibration patterns caused by imbalance are also predictable theoretically as are the vibration patterns exhibited by various faults occurring in rolling contact and journal bearings.

In reality however, mechanical system nonlinearities due to friction, gaps, stiffness discontinuities, and damping all yield inaccuracies in theoretical predictions. This is largely because these qualities are difficult to model and small changes between the model and reality yield significant differences between predicted and actual system behavior. For imbalance, and misalignment, this inaccuracy is negligible for most cases, but it can be a dominant factor in some cases. For bearing problems, both rolling contact and journal, the nonlinearities contribute extensively to the pattern of vibration and yield significant variation in the vibration spectra exhibited as a fault progresses in severity.

Empirical means of fault modeling bridge the gap between theoretical and actual fault indications. Vibration, temperature, and other measurements made prior to machinery breakdown and subsequent machinery repair feedback are an invaluable source of mechanical fault modeling. In these cases, the fault model is not a model at all, but is the actual machine with an actual fault. It serves as a model for similar faults as they occur in identical and other similar machines.

Theoretical fault modeling demonstrates forms which the data should take when a given fault is present and empirical methods bridge the gap by demonstrating the unpredictable variations from theory which occur in reality.

The empirical fault models available in the vast DLI Engineering database of vibration measurements, accompanying manual analyses, repair histories, and gauge readings spanning hundreds of naval vessels, thousands of machines and tens of thousands of machine tests have been used to create a very accurate and broad scope diagnostic ruleset. The initial MPROS design includes the existing vibration diagnostic ruleset, and empirical methodology. This, backed up by the theoretical modeling, will refine the rules to optimum accuracy using all available data inputs.

Initial Prototype Systems

Currently there are three Initial Prototype Data Concentrator (IPDC) systems installed and operational. The first is monitoring a York 400 ton Air Conditioning (A/C) chill water system located on the hospital ship USNS Comfort in Baltimore MD. The second is monitoring a Carrier 340

ton A/C chiller system at the Honeywell Technology Center (HTC) in Minneapolis MN. The third system is monitoring a York 360 ton A/C chiller system on board the aircraft carrier USS Abraham Lincoln (CVN 72).

Although MPROS is applicable to any type of rotating machinery, A/C chill water systems were chosen for these initial systems because of the wide range of applicability in industry, the fairly complex nature of the machines, and the broad field of faults that can be detected and diagnosed. A/C chill water plants typically have a widely varying set of operating conditions which are a function of the cooling requirements of the building or ship. A/C system load is usually related to the season of the year and the time of day. Shipboard systems also experience the additional effects of traveling between various climates of the world and are typically designed for the worst case cooling load, which may be experienced only a few times during the life of the unit. Figure 3 shows the typical layout of a marine A/C chill water system based on a centrifugal vane compressor and Figure 4 shows a mechanical schematic of a typical centrifugal vane compressor used in this type of system.

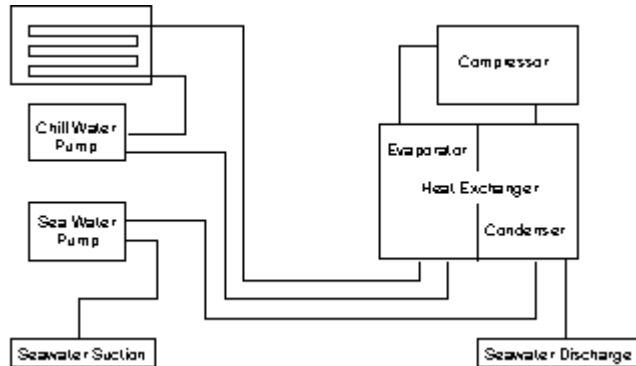


Figure 3 - Marine A/C Chill Water System

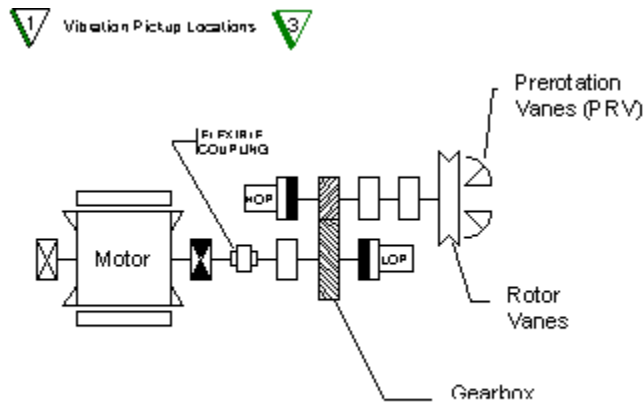


Figure 4 - Centrifugal Compressor Schematic

Architecture

The IPDC data acquisition hardware is based on the DLI Engineering Watchman FULLTIME monitoring system. The IPDC data analysis software is a modified version of the DLI Engineering ExpertAlert software.

This monitoring system consists of two basic parts. The first is a stand-alone programmable data acquisition, processing, and storage system which is contained inside a NEMA 4x enclosure and is located in the same machinery space as the machines to be monitored. Data stored in the unit is downloaded, and the unit is programmed, through an RS-232 link to a standard Personal Computer (PC). For this installation a laptop computer is mounted inside another enclosure and permanently connected to the unit. The basic layout of this system is shown in Figure 5. The computer is running a modified version of the ExpertAlert software and provides on-line machinery diagnostics based on the data collected.

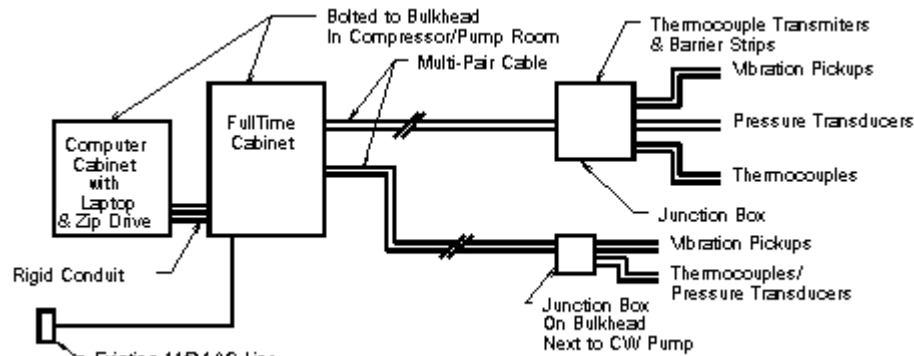


Figure 5 - Monitoring System Layout

For the shipboard systems each collected data set and diagnosis is sequentially archived with a date and time stamp onto a ZIP disk which is replaced on a monthly basis by shipboard personnel. The data are then sent back to the project team for detailed analysis. For the system at HTC the archived data and diagnosis is automatically transferred on a regular basis to the Honeywell anonymous ftp site where it is retrieved electronically via the Internet.

Sensors

The second part of the monitoring system consists of the sensors and/or process parameter inputs along with any required signal conditioning. Sensors were chosen, and are strategically mounted on the machinery, to optimize the information that can be obtained about machine condition and operating state. These sensors are wired into a junction box mounted on the machine platform and a single multi-conductor cable carries the signals back to the data acquisition system. The sensors and process parameters that are monitored at these installations are detailed below.

Single axis piezoelectric accelerometers are mounted in a triaxial configuration (three orthogonal measurement axes) and are installed on the compressor motor, compressor housing, chill water pump motor and the chill water pump housing. Overall vibration levels from 10 Hz to 20 kHz and both high (0-6000 Hz) and low range (0-600 Hz) spectra are acquired from each of the vibration sensors.

A single phase of compressor motor current is monitored with a current transformer located in the motor control cabinet. This provides a measure of compressor load as the current draw of the motor is directly proportional to the amount of work the compressor is performing. An upgrade to these prototype systems will monitor all three phases of motor current as well as the differential voltages between the phases and will allow for more detailed electrical signature analysis. The overall rms value of the motor current is acquired as well as high resolution motor current spectra.

There are four process temperatures that are measured: Chill water inlet and discharge and condenser (sea) water inlet and discharge. There are two process pressures that are measured: Chill water inlet and condenser water discharge. Each monitored temperature and pressure is measured as a single value for a given data acquisition cycle and used for trend analysis and in the correlation of the vibration measurements with a given process state.

PreRotation Vane (PRV) Position is monitored using a string potentiometer attached to the PRV control linkage on the outside of the compressor. The pre-rotation vanes act like a throttle on the suction side of the compressor and control compressor load (see Figure 4). Like the temperatures and pressures a single value is recorded for a given data acquisition cycle.

Machinery Fault Model

Current fault models are based solely on vibration signal analysis. The intent of this prototype project is to modify the fault models to include the process information and to study the behavior of the vibration patterns versus changing process parameters. The following section describes the fault modeling done in the existing vibration based system.

DLI Engineering Expert Rulebase

The expert system uses triaxial narrow band spectra from several points near the bearings of the rotating components of the system. The speed of each component is determined, then features are extracted from the spectra and diagnostic rules are applied to the features.

Feature extraction goes beyond determination of the vibration levels at specified frequencies. Algorithms group harmonics and subharmonics to help determine looseness characteristics. Cepstrum based methods are used to determine if non shaft synchronous peaks are bearing tones. Envelope detection is even used in some applications to determine the existence of bearing faults. Further more, the feature extraction process is different for each component type. The kinds of features extracted when checking signals from a motor are different than those extracted when examining a pump or a compressor.

The set of features is extensive and is assembled into a matrix form known as a Component Specific Data Matrix (CSDM). Diagnostic rules are then applied to the elements of the CSDM to check for patterns which indicate the presence of a fault. A simple example is the rule for imbalance which checks the CSDM elements containing the rotational rate levels and exceedances over average and determines whether they are high in the radial direction. If so other checks determine that the problem is not misalignment or looseness and then the imbalance diagnosis is confirmed. These diagnostic rules were developed and tested on a database of tens of thousands of machine vibration tests.

The list of faults that the expert system is currently capable of detecting is provided in Table 1. Our intention is to introduce process parameters into the CSDM and modify the rulebase to check these elements in conjunction with vibration features when performing its diagnostics.

Table 1 - A/C Compressor Faults

COMPONENT TYPE=MOTORS

- MOTOR MOUNTING FLEXIBILITY
- MOTOR BEARING LOOSENESS
- MOTOR THRUST BEARING LOOSENESS
- MOTOR BEARING MISALIGNMENT
- MOTOR ROTOR BAR PROBLEM
- MOTOR STATOR ECCENTRICITY OR LOOSENESS
- MOTOR AIR GAP PROBLEM
- MOTOR BEARING WEAR
- INDICATION OF POSSIBLE MOTOR BEARING WEAR
- MOTOR IMBALANCE
- MOTOR BEARING NOISE
- MOTOR FOUNDATION RESONANCE OR MOUNTING LOOSENESS
- MOTOR BALL BEARING DEMOD
- MOTOR BALL BEARING SIGNIFICANT DEMOD

COMPONENT TYPE=FLEXPLG

- MOTOR TO GEARBOX PARALLEL MISALIGNMENT
- IRREGULAR AXIAL MOVEMENT OF DRIVER AT COUPLING
- IRREGULAR AXIAL MOVEMENT OF DRIVEN COMPONENT AT COUPLING
- MOTOR TO GEARBOX ANGULAR MISALIGNMENT
- MOTOR TO GEARBOX COUPLING WEAR

COMPONENT TYPE=GEARS

- MAIN GEAR MESH PROBLEM OR WEAR
- GEARBOX NOISE
- UNSPECIFIED GEARBOX PROBLEM
- GEARBOX LOW SPEED SHAFT OIL PUMP INTERNAL WEAR
- GEARBOX INPUT SHAFT DEMOD
- GEARBOX OUTPUT SHAFT JOURNAL WEAR OR GEAR DAMAGE

COMPONENT TYPE=CENTCPRS

- COMPRESSOR IMPELLER WEAR OR CLEARANCE PROBLEM
- COMPRESSOR JOURNAL WEAR
- COMPRESSOR JOURNAL BEARING LOOSENESS
- COMPRESSOR IMBALANCE
- COMPRESSOR FLOW DISTURBANCE
- COMPRESSOR GUIDE VANE PROBLEM
- MAIN COMPRESSOR SHAFT JOURNAL BEARING OIL WHIRL
- UNSPECIFIED COMPRESSOR END PROBLEM
- COMPRESSOR OIL PUMP INTERNAL WEAR
- COMPRESSOR OIL PUMP DRIVE GEAR MESH PROBLEM

Future Development

There are many technologies that have not been implemented in the initial prototype systems which are expected to be incorporated into future systems. The following is a short, and by no means exhaustive, list of some of the features and technologies that will be developed for MPROS. The architecture of

MPROS allows for the inclusion of new and different techniques as they are required or become available.

- Microsensors for detecting wear particle concentrations on-line are currently being developed and should be available for use in a future generation of MPROS. Trending of wear particle concentrations will contribute a significant amount of information about the machine condition that cannot be obtained by other means. Incorporation of this data into the diagnostic and prognostic models will greatly enhance the accuracy of fault identification and remaining life predictions.
- The next generation of prototype systems will monitor three phases of motor current as well as the differential voltages between phases. This provides data for the implementation of electrical signature diagnostic algorithms, the results of which will be integrated into the diagnostic and prognostic analysis.
- Improved data concentrator hardware is currently under development which will simplify and reduce the size of the current prototype systems by more than fifty percent. The size of the data concentrators is expected to continue to shrink as the hardware becomes more customized for this application.
- Honeywell is developing MEMS (micro electro-mechanical systems) sensors for use with MPROS. MEMS temperature sensors are now available and in use at the HTC installation. Pressure, strain and acceleration sensors are expected to become available over the next year or so.
- Work is underway to determine the feasibility of using wireless technologies for linking sensors to a DC. This would eliminate the need to hardwire all of the machines to be monitored on a ship and could significantly reduce the labor required to install these systems onto existing machinery.
- Work is being done on the development of the prognosis engine that will operate in conjunction with the diagnostic systems currently in prototype development. Many good algorithms and methods such as neural networks and state based feature recognition exist and will provide the high level of data fusion required for accurate condition based machinery prognostics.

CASE STUDY

Introduction

This study is based on data collected by the Initial Prototype Data Concentrator (IPDC) system installed on Chiller #3 at the Honeywell Technology Center in Minneapolis Minnesota.

Several relationships have been observed between the compressor vibration signatures and chiller system process parameters which allow for a more accurate interpretation of the vibration signatures and a more refined expert system model of the chiller. It was found that when low amplitudes of compressor motor current were recorded, the compressor vibration spectral data exhibited a unique signature which has been attributed to a condition referred to as "stall". Low amplitudes of motor current indicate that the chiller system load is low. Low system load results in inefficient flow through the compressor discharge scroll which causes pulsation of the refrigerant fluid and produces a vibration signature which deviates significantly from those obtained during high load conditions. This situation is not considered a fault condition by the compressor manufacturer and in fact is considered quite normal for these units.

The problem encountered here is that the vibration signatures associated with "stall" are similar to the signatures associated with several fault conditions such as bearing wear and motor electrical problems. This introduces the need to know what load condition the chiller system is experiencing when vibration data is collected and analyzed, and what relationship exists between system load and the vibration signatures. If these relationships are known then they can be implemented into the expert system model and a much more accurate automated analysis of the machinery condition can be made.

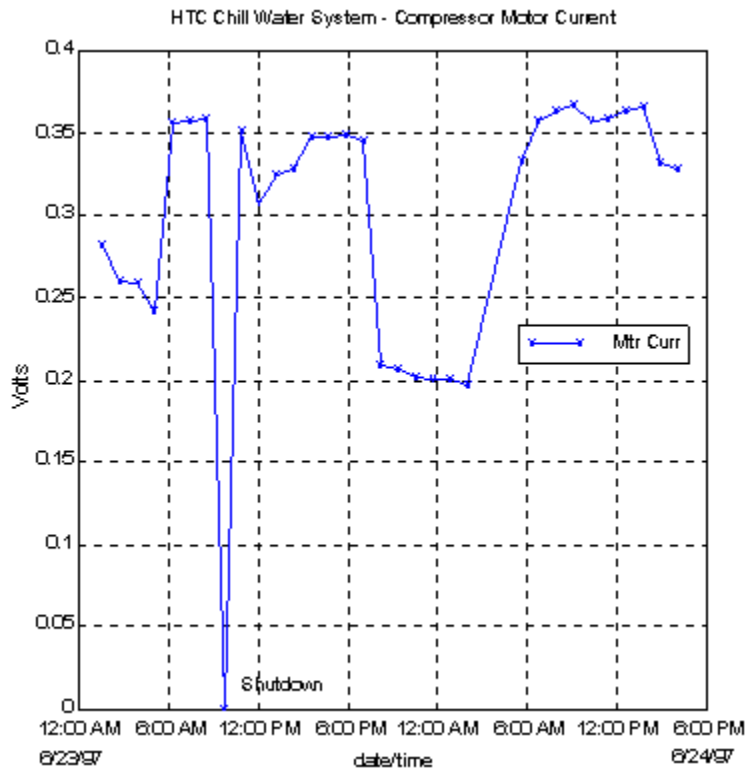


Figure 6 - Compressor Motor Current

Data analysis

Figure 6 shows a plot of compressor motor current during a typical 36 hour period. From this plot it can be clearly seen that after 7:00pm compressor load drops to a very low level and stays low until 2:00am the next morning before it rises again to amplitudes that indicate the system is loaded and producing chill water.

Figure 7 shows a trend of compressor overall or broadband vibration through this same overnight period. A marked increase in vibration levels can clearly be seen in Figure 7 during the overnight period. Figure 8 is a waterfall plot of narrow band spectra vibration measured at the Compressor Coupled End Radial during this overnight period. Comparison of Figure 6 with Figure 8 reveals the changes in the vibration signatures which occur as a result of the low system load as indicated by the compressor motor current. An increase in 1.5x (90 Hz) compressor motor speed vibration can be identified as well as an increase in the overall noise floor of the spectral data at frequencies below about 400 Hz. This increase in the low frequency noise floor is the most likely cause of the increase in overall vibration levels at low compressor load that is seen in Figure 7.

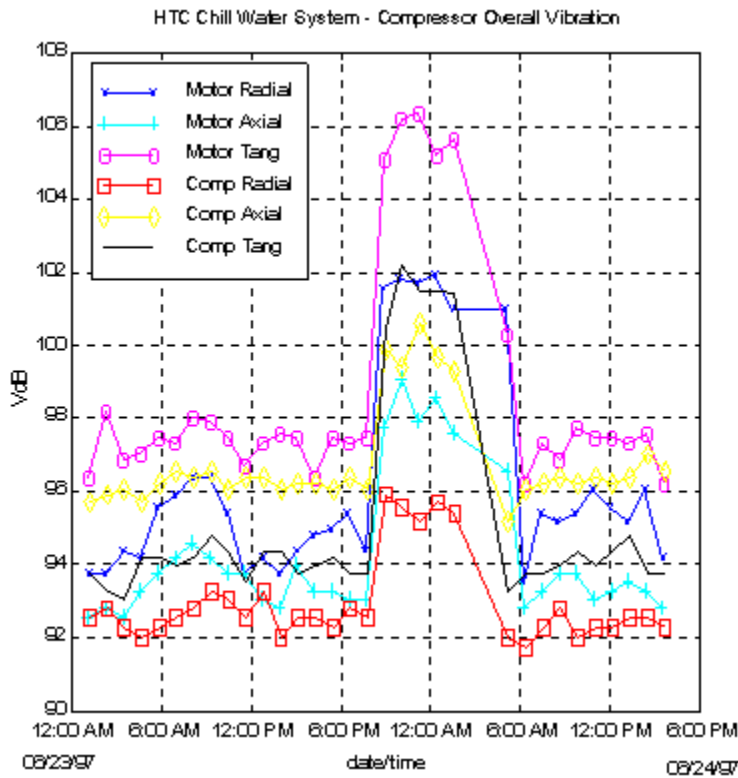


Figure 7 - Compressor Overall Vibration

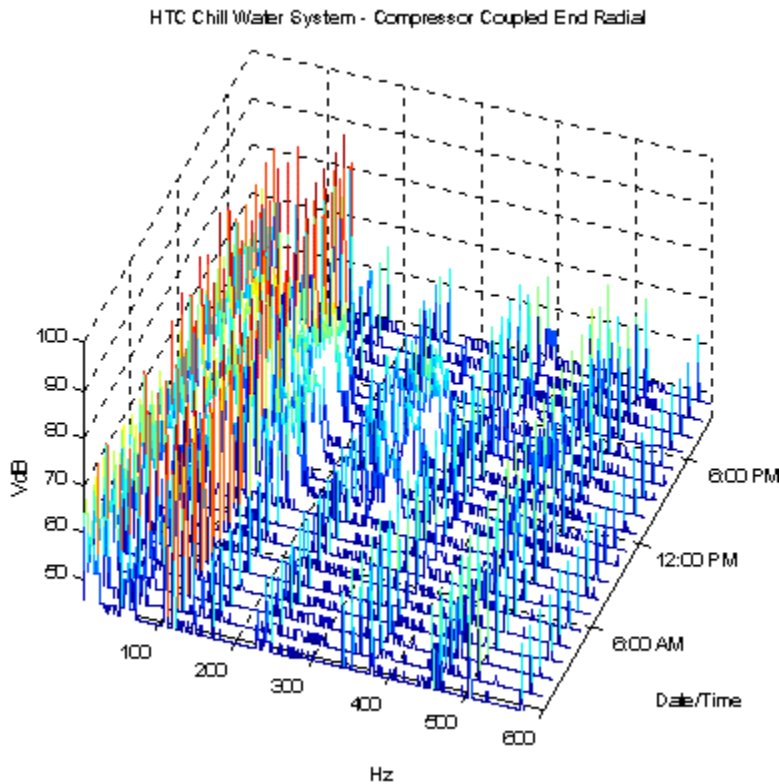


Figure 8 - Compressor Vibration

Figure 9 shows the temperature differential (ΔT) across both the evaporator and the condenser. This plot indicates the low load conditions that occur during the overnight period which appear as a reduction in the temperature differential across the two heat exchangers. A small ΔT indicates a lower amount of heat transfer for a constant flow rate and hence a reduction in the amount of work being

performed by the compressor. This data provides supporting evidence for the strong relationship between motor current and system load and can also be used to evaluate heat exchanger inefficiency and fouling.

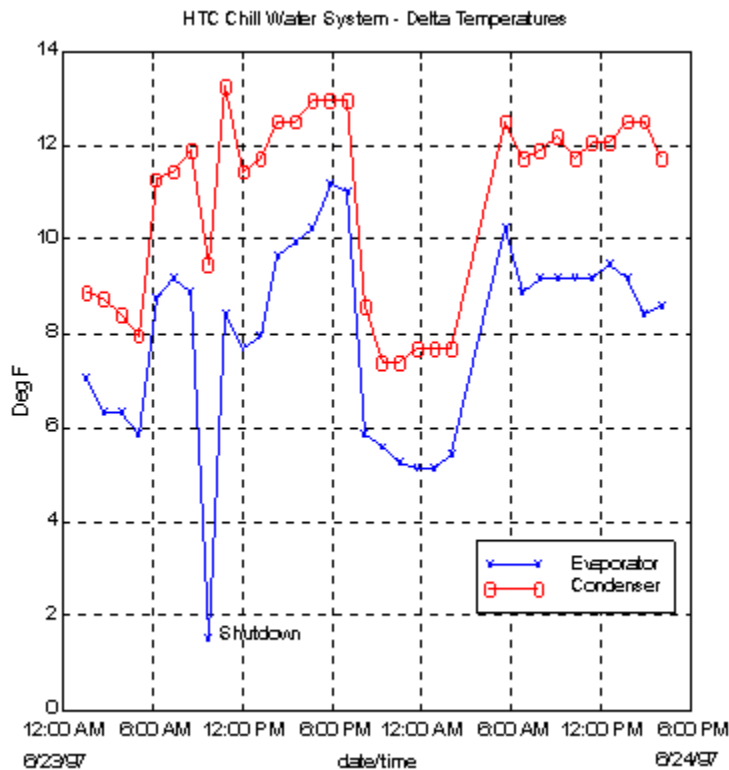


Figure 9 - Differential Temperatures

In this case motor current amplitude by itself provides enough significant information about chiller system load to allow the modification of the vibration analysis rulebase so that a more accurate analysis of the compressor vibration signatures under light load conditions can be obtained.

Conclusions

Further case studies will undoubtedly allow us to build a library of normal and abnormal combinations of process parameters and vibration measurements to enable accurate diagnostics and provide the in-depth data that is needed to support prognostics.

Accurate prognostics for machine life prediction will only follow from a wealth of this type of multi-variant performance monitoring histories. There are many prognostic algorithms based on theoretical principals which must be tested and refined using consistent and accurate data acquired from machines as they are subjected to real operating conditions. The MPROS system provides a platform on which to implement and refine the complex prognostic algorithms required to achieve accurate prediction of remaining machine life.

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