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Acoustic Based Sensing for Condition Based Maintenance

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ABSTRACT

Curtiss-Wright has developed an acoustic based sensor technology for measuring friction, shock, and dynamic load transfer between moving parts in machinery. This technology provides a means of detecting and analyzing machine structure borne ultrasonic frequency sounds caused by friction and shock events between the moving parts of the machine. Electrical signals from the sensors are amplified and filtered to remove unwanted low frequency vibration energy. The resulting data is analyzed as a computed stress wave energy value that considers the amplitude, shape, duration and rates of all friction and shock events that occur during a reference time interval. The ability to separate stress waves from the lower frequency operational noise makes this technology capable of detecting damaged gears/bearings and changes in lubrication in equipment earlier than other techniques, and before failure progression increases cost of repair. Already TRL9 in adjacent industries, this technology offers great costs saving potential for military ground vehicle maintainers.

INTRODUCTION

This document describes a mature high Technology Readiness Level (TRL) diagnostic and prognostic technology developed by Curtiss-Wright which is currently deployed in industrial and naval applications. It measures friction between moving parts in rotating machinery and can detect and measure damage levels well below the degradation required to excite vibration sensors, and before sufficient damage has occurred to activate metal chip detectors in lubrication systems. Because of its ability to detect changes early in the failure process, assessments including true health status and remaining useful life are possible. In addition, the technology permits not only fault detection, but fault isolation to individual components.

By measuring friction, Acoustic-based Prognostics for Condition Based Maintenance (CBM) provides a unique diagnostic and prognostic capability that is ideal for condition monitoring of rotating machinery such as transmission final drives, gearboxes, motors, pumps and turbines. It can also work well on machine types such as slow speed, partial cycle and reciprocating machines that traditionally have been difficult to monitor.

VEHICLE HEATH MANAGEMENT SYSTEM USING ACOUSTIC BASED PROGNOSTICS

Theory of Operation

Acoustic-based prognostics is a state-of-the-art instrumentation technique for measuring friction, shock, and dynamic load transfer between moving parts in rotating machinery. It provides an electronic means of detecting and analyzing sounds that travel through a machine structure at ultrasonic frequencies. As machine parts come in contact with a defect, even at the earliest stages, shock and friction events generate Stress Wave Energy (SWE). The Curtiss-Wright prognostics system detects and measures this energy at damage levels well below the degradation required to excite vibration sensors, and before sufficient damage has occurred to activate metal chip detectors in lubrication systems. An externally mounted sensor on the machine's housing detects stress waves transmitted through the machine's structure. A piezoelectric crystal in the sensor converts the stress wave amplitude into an electrical signal, which is then amplified and filtered by a high frequency band pass filter, to remove unwanted low frequency and sound and vibration energy.

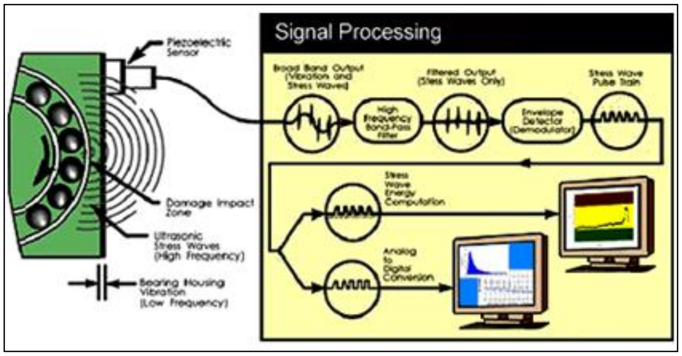

Figure 1: State-of-the-art technique for friction measurement

The output of the signal conditioner is a Stress Wave Pulse Train (SWPT) that represents a time history of individual shock and friction events that have occurred in the machine. A Digital Signal Processor then analyzes the SWPT to determine the highest amplitude and the total energy content generated by the friction/shock event. The computed Stress Wave Peak Amplitude (SWPA) and Stress Wave Energy (SWE) values are displayed and stored in a database for historical trending, analysis and contact surfaces. The level and pattern of anomalous shock events becomes a diagnostic tool.

The digital analysis of stress waves consists of computing both the amplitude and the energy content of detected stress waves. The amplitude (or peak level) of a stress wave is a function of the intensity of a single friction or shock event. The Stress Wave Energy (SWE) is a computed value (the time domain integral) that considers the amplitude, shape, duration and rates of all friction and shock events that occur during a reference time interval. In a spalled bearing, for example, the peak level of the detected stress waves is primarily a function of the spall depth, while the SWE is a function of spall size, as shown in Figure 2.

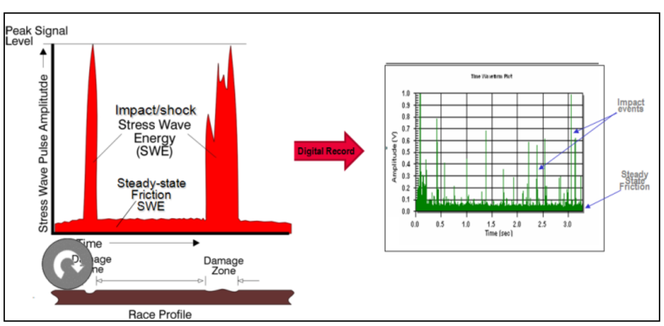

Figure 2: Example of spalled bearing and conversion from SWE to digital record

The ability to separate stress waves from the much lower frequency range of operating machinery vibration and audible noise makes the Curtiss-Wright prognostics system an indispensable tool when monitoring operational equipment for damaged gears and bearings. In most cases, during early component fatigue, the energy released between the contact surfaces is too small to excite gearbox or engine structures to levels significantly above background vibration levels, until catastrophic failure or extensive secondary damage occurs. However, with acoustic based prognostics, Stress Wave Energy can be detected and analyzed early in the failure process, as demonstrated in Figure 3. This will detect degradation of mission critical components well before catastrophic failures occur and support true conditioned based maintenance activities.

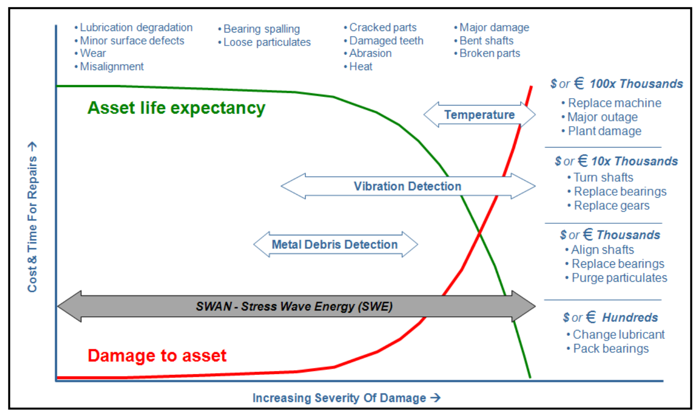

Figure 3: Failure Progression Chart Mapped To Failure Detection Technology

Acoustic Based Prognostics System Components

The acoustic based prognostics system is comprised of the following components, see Figure 4. The following section provides descriptions of each component.

- Acoustic Stress Sensors
- Stress Sensor Cables
- Acoustic based Prognostics Electronics
- Acoustic based Prognostics Software

Figure 4: System Components

Acoustic Stress Sensors

Acoustic Stress Sensors are specially designed with a piezoelectric element and built-in electronics. These sensors, when excited by ultrasonic stress waves, produce an output voltage signal that is proportional to stress wave signal intensity. The sensors must be firmly mounted to the machine structure to ensure proper transmission of the stress wave.

Stress Sensor Cables

Power for the sensor's built-in electronics and the output signal are conducted over a common wire. This allows the use of a single shielded twisted pair cable connected to the sensor. Shielded twisted pair cables with circular threaded type connectors are provided with the acoustic based prognostics electronics. The output signal from the sensor is sufficient to drive cable distances up to 300 feet.

Acoustic Based Prognostic Electronics

In the industrial applications, the acoustic based prognostics electronics comes in a panel or wall mountable industrial enclosure. The assembly is suitable for use in NEMA 4, 12, or 13 environments. For military ground vehicle applications, the electronics have been repackaged and ruggedized to meet ground vehicle specifications. This rugged configuration has passed military vehicle environmental testing.

Acoustic Based Prognostic Software

The prognostics software provides a suite of application support software that is used to automatically and continuously communicate with the various machineries deployed around a vehicle/plant/facility/mill/ship for the monitoring of equipment mechanical condition, see **Error! Reference source not found.**Figure 5. This display and analysis package runs on a LINUX operating system.

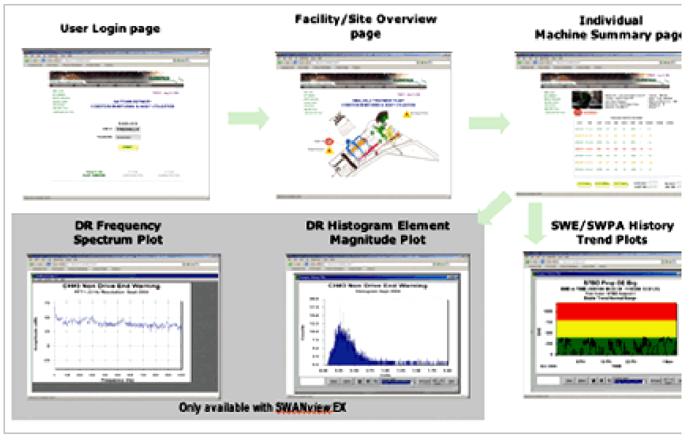

Figure 5: Prognostic Software Screen Shots

The prognostics software includes display tools for analyzing the digital records (DR) collected by the acoustics based prognostics electronics modules when SWE anomalies are detected. Although a time trend of SWE provides a good overall indication of machine health (or failure progression), performing an analysis on the DRs can also aid in identifying the type and source(s) of mechanical deterioration. The histogram plot allows the identification of lubrication problems and, in combination with the SWE and frequency spectrum plot, can identify the presence of excessive wear and physical damage. The frequency spectrum plot provides a good means for identifying physical damage, identifying cavitation and, if combined with RPM data and manufacturers bearing defect frequencies, can identify specific bearing components (rolling elements, raceway) that are generating the SWE signals being detected. This has direct application to power train, suspension and turret drive components.

The prognostics software has several additional displays that can be used in applications where process measurements and operational parameters related to machine performance and loading are available to the user. These displays provide correlation between SWE levels and process parameters, thus providing a means for asset life optimization and development of best in class operational procedures related to asset optimization.

TECHNOLOGY READINESS LEVEL (TRL) SELF ASSESSMENT SUMMARY

The prognostics system is currently in daily operation of Marine/Cruise Ships, Fossil Power Plants, Wind Turbines, Refinery & Petro Chemicals, Pipeline Pump/Compressor Stations, and Aerospace applications. In all these applications the system (including sensors, electronics, software, and cables) is at TRL 9 (defined as: Actual system proven through successful mission operations)

Deployment for Operational Readiness

For the past ten years the acoustic based prognostics system has been deployed by the US Navy in the pre-deployment health assessments process. The craft does a high speed engine run up for 5 minutes (parked), then the data is analyzed and a decision is made to either return the craft to service, clear it for duty at sea, or schedule maintenance. This tool is useful in assessing operational readiness of a craft that has its life extended beyond its original mandate.

Figure 6: Acoustic based Prognostics Deployed by the US Navy

Although the acoustic based prognostics system is widely deployed in industrial and marine applications, for the TRL self assessment, the marine application was chosen to reflect an onboard architecture that can be applied to your Program. The prognostics system is deployed on over 38 Ocean Liners in daily operation including the Queen Mary II Main Engines, see Figures 7 through 10.

Fig. 7: Queen Mary II

Fig. 8: Ship PODs

Figure 9: Onboard Acoustic based Prognostics System

Figure 10: Acoustic based Prognostics POD monitoring software Graphic User Interface

The acoustic based prognostics system is an onboard system that accurately assesses the operating health of the ship's mechanical systems. These systems include:

- Azimuth & Fix Podded propulsion drives (POD)
- HVACs
- MGs
- PEMs
- Main GBX
- POD Cooling Fans

This onboard system has an open web-based architecture and integrated ship automation capabilities for real-time health management information. Figure 11 provides the acoustic based prognostics system architecture as it is deployed on the ships.

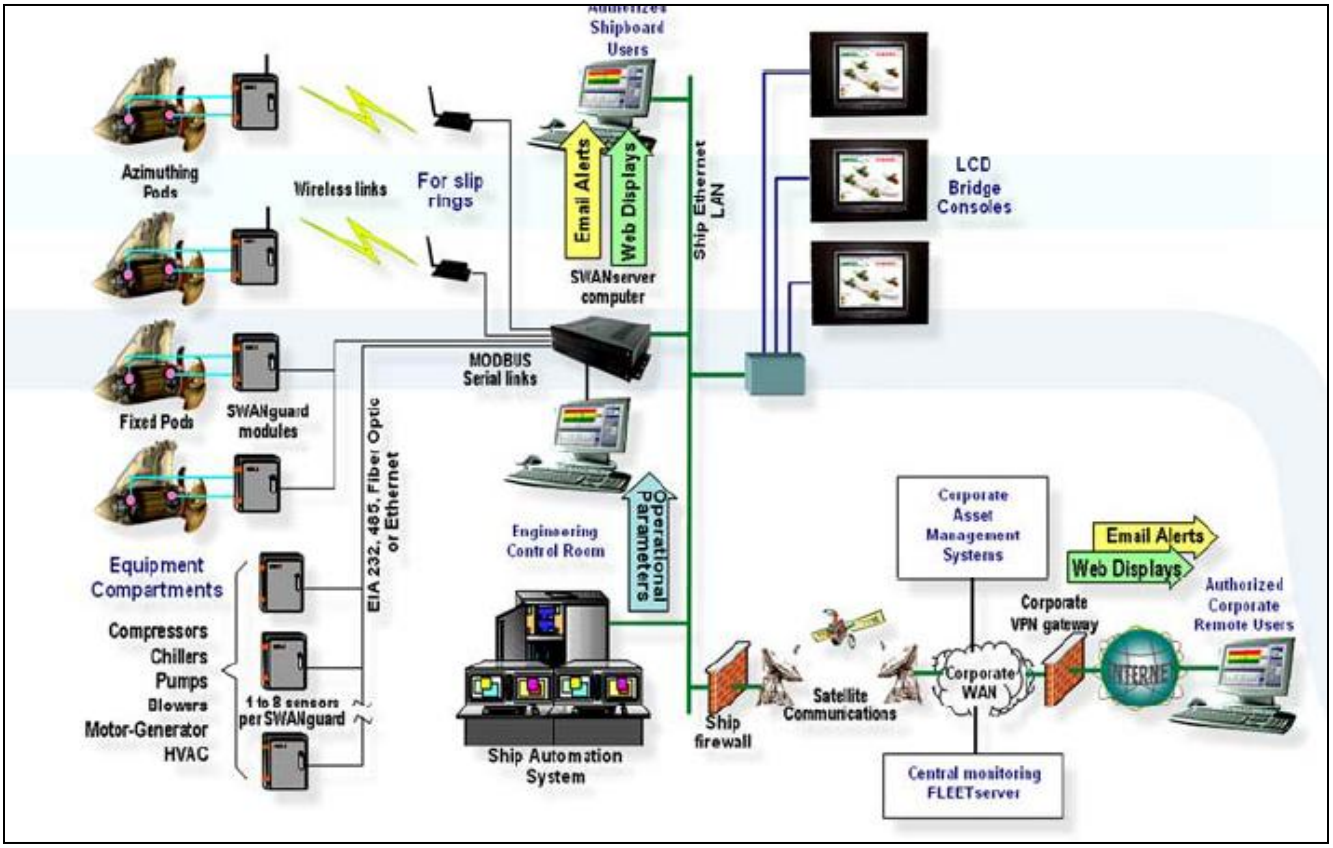

Figure 11: Prognostics System Onboard Health Management Architecture on Ships

Marine Application Case Study

Podded propulsion drives (POD) have proven their worth in the cruise line industry. Enhancements in ship operations such as greater maneuverability, space savings, low vibration levels and greater power plant efficiency as well as reduced pollution are expanding the use of these drives on other marine craft, including military ships, ferries and tankers. The costs of failure and the resulting unscheduled maintenance start in the millions of dollars. The very elegance of the podded drive's sealed design makes it difficult to monitor and analyze. The acoustic based prognostics technology provides an onboard real time health management system to these critical mechanical systems. To date, the deployed prognostics systems have confirmed detection of the following POD anomalies:

- Main bearing spall (thrust and radial)
- Main bearing cracks (sub-surface)
- Outer and inner race cracks
- Cage rub
- Propeller imbalance
- Propeller milling (ice)
- Seal misalignment
- Seal wear
- Lubrication degradation or failure
- Leaking heat exchanger
- Water contamination
- Excessive loading as function of power, RPM, steering angle, currents, etc.
- Shaft imbalance as function of Pole pass

In addition to monitoring the critical mechanical system, the prognostics system also monitors the auxiliary mechanical system. Within this category, the acoustic based prognostics system has confirmed detection of anomalies in the following systems:

- HVAC
  - Compressor screw wear
  - Main bearing wear
  - Inoperative speed/load sensor,
- Motor Generator,
  - Main bearing wear
- Pump & Fan
  - Main bearing wear

The electronics are repackaged and ruggedized to meet ground vehicle specifications. The electronics have passed environmental testing per Bradley Fighting Vehicle temperature and vibration specifications.

CONCLUSION

Acoustic based Stress Wave Energy sensing technology provides the earliest indication of actionable mechanical system health issues for cost-effective condition-based maintenance and integrated vehicle health management. It is a proven TRL9 technology in applications such as cruise ships, Navy LCAC vessels, wind farms, and industrial manufacturing.

Curtiss-Wright has projects under way to demonstrate it’s effectiveness on military ground vehicle applications. At the writing of this paper projects under way include sensing health degradation on multiple Bradley Fighting Vehicle transmissions in a dynamometer lab based highly accelerated life test, and sensing Light Armored Vehicle wheel differential health degradation due to intrusion of impurities such as water and sand.