Y-12

OAK RIDGE Y-12 PLANT

LOCKHEED MARTIN

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High Throughput and Reliability (HITaR)

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ABSTRACT

Historically, companies have used transfer lines to produce high volumes of commercial and defense application products. Because the transfer line is composed of custom machinery to produce a specific part type, it is no longer a cost-effective means of manufacturing in the current environment of frequently changing parts produced in small lot sizes. With reliability and throughput improvements, job-shop oriented computer numerical control (CNC) machining centers can meet today's needs of the high volume, high reliability production environment. The purpose of this CRADA was to improve the throughput and reliability of Cincinnati Millicron machining centers to fulfill these needs. A new Cincinnati Millicron product, the Magnum Machining Center, was evaluated at Y-12 for this purpose. The throughput and reliability improvements were accomplished through machine upgrades, machinability studies to improve material removal rates, and implementation of a sensor based predictive maintenance system.

CRADA Objectives

The objective of this CRADA was to improve the throughput and reliability of machine tools by increasing machine dependability, increasing material removal rates, and developing a predictive maintenance system to alert users of impending machine failures. The test-bed used was the Magnum Machining Center, a new Cincinnati Milacron product line.

The major objective of improving throughput and reliability was met through three smaller objectives. The first was to evaluate the overall reliability of this machine and work with Cincinnati Milacron to address reliability problems. The second was to machine at increasingly high material removal rates while monitoring the machine for signs of degradation. The third involved the installation of "predictive" sensor systems on the machine to detect deviations from normal operating conditions. These systems would alert personnel of impending machine component failures. This would allow maintenance to be scheduled and performed in a controlled manner rather than having a machine break down unexpectedly.

The objective of working with Cincinnati Milacron to improve the reliability of the machine was met. Although there were no major reliability problems identified, work was done to study and improve the thermal stability of the machine.

The second objective was met. Some preliminary machinability studies were done using cast iron and steel hardened to Rockwell 60. The real success came when the machine was used to produce a series of parts for the DOD using higher feedrates than the feedrates used to produce the same parts on other machine tools. The fabrication times for the parts was reduced from 21 days to seven days.

The third objective was partially met. A laboratory grade predictive maintenance system was developed, demonstrated, and used. Funding constraints prevented this system from being made robust enough to be placed on a production shop floor. The system is mature enough that future predictive maintenance tasks will be able to use much of the technology developed in this CRADA.

DOE Benefit

The technology developed for the predictive maintenance system will be used in future predictive maintenance tasks. This technology is important to DOE in the present environment of a reduced factory with a reduced workforce, where each machine could be the single point of failure in a production line. The ability to identify and correct a problem before it stops production will benefit DOE.

The thermal stability testing helped maintain the Plant's capability to set up, run, and evaluate this type of machine test.

Technical Discussion

Equipment

Magnum Machining Center

The Magnum, shown in figure 1, is a horizontal machining center having a work volume of approximately one cubic meter. It has three linear axis plus a contouring rotary axis, a 135 pocket tool changer, and six station automatic workpiece changer. It is controlled by an Acromatic 950 controller. The spindle can produce 50 horsepower, and run at 10,000 RPM. The machine was delivered to Y-12 in June of 1995 and installed in building 9737.

Figure 1. Magnum Machining Center and Data Collection Computers

Data Collection Computers

A general overview of the data collection system is shown in figure 2. Due to the large number of data channels being collected, two computers were used. Data was exchanged between these

Figure 2. Data Collection System

computers via ethernet connection. One computer, System 1, was dedicated to collecting temperature and spindle horsepower data. The other computer, System 2, collected electrical current and accelerometer data. System specifications are shown in Table 1, both data collection boards were manufactured by National Instruments.

Table 1. Computer System Specifications

	Processor	Memory	Hard Disk	Data Collection Board
System 1	Pentium 90	32 MB	1 GB	ATMIO64F5
System 2	Pentium 133	80 MB	2.5 GB	ATMIO64E3

It should be noted that these computer system were adequate when they were purchased, but as the predictive maintenance system became more complex and demanding, the computer performance was marginal.

Software

Programs written using National Instruments Labview version 4.01 were used for data collection and some of the data analysis functions. Other data analysis was performed on software compiled on Microsoft Fortran version 4.0 for Windows.

Signal Conditioning

Two Omega OM3 Series racks were installed on System 1, which was used for temperature monitoring. Omega OM3-ITC-J signal conditioning modules were used for thermocouples, OM3-IP-100 modules were used for the RTDs. There was also a OM3-IMV-10 isolated voltage input signal conditioner that was used for spindle horsepower measurement. All inputs on system 2 were amplified to a 0 to 10 volt range, low pass filtered to eliminate signal aliasing, and tied directly into the data collection board. The low-pass filter cut-off frequency was 1 KHz for accelerometers, and 20 KHz for the current sensors.

Sensors

Temperature - Fourteen type J thermocouples, and 16 RTDs were strategically placed on the machine. Three of the thermocouples were installed in the spindle by Cincinnati Milacron, one on each of the main bearings. Data from these temperature sensors were acquired by System 1. All temperature sensors were calibrated by the Plant's Standards Lab.

Motor Power - The Magnum controller had a spindle horsepower monitor embedded in it that had a 0 to 10 volt output proportional to the spindle motor horsepower. This voltage output was monitored by System 1, allowing the temperature data to be correlated with spindle horsepower.

Electrical Current - Electrical current was sensed using inductively coupled devices manufactured by Microswitch. These devices slip on over the current carrying conductor. Model number CSLA1CD devices were used on all motors except the spindle where a CSLA1DG was used. Output from these devices was amplified, low-pass filtered, and input to the System 2 computer.

Vibration - Eight IRD Mechanalysis 942 accelerometers were used. These were embedded in the spindle housing and glued to X-Axis components. Accelerometer outputs were conditioned by

four-channel Kistler Power Supply/Couplers, type 5134.

The location of current sensors and accelerometers is given in Tables 2 and 3.

Table 2. Electrical Current Sensor Location

Hydraulic Oil Chiller
Hydraulic Pump Motor
Coolant Pump Motor
Chip Conveyor
Chip Auger 1
Chip Auger 2
Spindle Motor
X-Axis
Y-Axis
Z-Axis
B-Axis
Work Changer Rotary Axis
Tool Changer Chain

Table 3. Accelerometer Location

Location	Orientation
X-Axis Lead Screw Bearing	Along the screw axis, screw thrust direction.
X-Axis Lead Screw Bearing	Perpendicular to screw axis.
X-Axis Truck Rail	Parallel to truck travel.
X-Axis Truck Rail	Perpendicular to truck travel.
X-Axis Ball Nut	Parallel to lead screw
X-Axis Motor Housing	Parallel to lead screw
Spindle Snout	Vertical
Spindle Gear Rear	Vertical

Thermal Stability Test

Two types of thermal stability tests were run. One was a ball mounted on the spindle as shown in figure 3, the other was the Cincinnati Milacron gage nest shown in figure 4. For the ball test, a LabView program was written on computer system 1 to collect, record, and display temperature and capacitance probe displacement data. The gage nest was equipped with a stand alone portable data collection computer that would record LVDT and two channels of temperature data. Computer system 1 was used to collect additional temperature data during the gage nest test.

During a ball test, the Magnum spindle was run at a specified RPM while capacitance probe and temperature data were taken. Plots of temperature vs time, and displacement vs temperature were generated. This test captured spindle growth data while the spindle was turning, but it only provided data in the three orthogonal directions.

The gage nest test involved zeroing the gage nest, storing the tool bar in the tool changer, and running the Magnum to simulate part cutting. At 15 minute intervals, the spindle was stopped, the gage bar retrieved from the tool changer, inserted into the gage nest, and LVDT and temperature data were taken. Data could not be collected while the spindle was actually turning, however the arrangement of pairs of LVDTs in the X and Y directions gave spindle pitch and yaw information.

All data was transmitted to Cincinnati Milacron for evaluation and will not be presented here. The benefit to DOE is not in the actual data, but in the experience with the gage nest test, and the development of LabView software that can be used to collect displacement and temperature data on other machine tools.

Predictive Maintenance System

The goal of the predictive maintenance (PM) work was to develop a system that could be used by the average man on the shop floor to evaluate the health of his machine and shop environment. This involves running a PM cycle on the Magnum to exercise the machine, collecting sensor data during the exercise, analyzing the data, comparing the analysis to baseline information, then turning on red/green indicators based on the comparison with baseline. Detailed information about the raw data and analysis can be viewed through additional screens.

Integration of the data collection computer with the Magnum 950 controller was necessary to coordinate data collection with machine motion. If, for instance, the machine was in the Y-Axis motion phase of the exercise routine, the data collection computer needed to know to read data from the Y-Axis current sensor. The coordination was achieved by installing a CRMCO board in the 950 controller. This board was populated with relays that could be operated by issuing "M" codes in the control program. Eight relays were connected to the digital IO port on the ATMIO64E3 board in the data collection computer. Seven of the relays were used for the controller to send a code to the data collection computer. The code defined the operation that was about to take place on the Magnum. The eighth relay was used as a trigger to tell the data collection computer to start collection. The computer screen shown in figure 5 was displayed during the exercise program/data collection phase of the PM cycle. It allowed the operator to verify that the 950 controller and the data collection computer were synchronized.

Since particular high failure or troublesome components could not be identified for this machine, it was decided to provide monitoring over the whole system. Sensors were selected to provide data on vibration at key points and to provide electrical signatures on the various motors operating in the Magnum system. This selection process produced 26 points and/or signals that needed to be sampled, including 12 vibration readings from the spindle and axis drive assemblies and about 14 current transformer readings from the system motors.

The system was originally desired to operate in a hands-off mode where the machine ran through a set of operations and data was taken automatically (refer to Figure 5 for a view of the Main Program front screen). After the data was acquired, the system would automatically analyze the data and present results in a variety of on-screen methods to an operator or analyst (Figure 5 also shows the main Analysis screen that is accessed from the Main Program screen). The software design was planned to require minimal operator interaction for simplicity. Later in the development various new options were discussed and several things were made more interactive to allow analysts or operators some ability to inquire into the analysis results. The addition of these options increased the complexity of the software in the form of linking between subroutines to allow the versatility desired. These changes were part of a normal development as the concept of what was really needed was massaged as the project moved forward.

The status of the development at this point is to incorporate the most beneficial options in the acquisition and analysis process. This really requires significant reorganization of the code to remove segments that are not needed to accomplish the final goals. This reorganization has begun but due to funding constraints is not complete. During the time that software development has been proceeding, data has been collected from the machine's various test points and digitally stored in a standard format. This standard format has been retained throughout the life of the project, so all the data can be referred back to for trending and analysis. During this time, there have been some major changes of components in the machine due to infant failures or upgrades. Although the software is being designed to perform long term trending and prediction, this type of analysis has not been heavily pursued yet. Efforts thus far have been focused on developing the right form of software architecture.

The architecture presently developed is shown in the block diagram format seen in Figure 6. The method of operation for the analysis software is presently set up to sample the various motors in the Magnum machine during a pre-programmed set of test runs. To initiate a data acquisition

session, the LabView software is set in the running mode and then the machine is commanded to run the standard tests. The software program then watches for "M" codes (digital codes) from the Magnum machine that identify which component is running, and the software samples and stores the appropriate data waveform.

After the waveform collection and storage is complete, the analysis can be either manually or automatically started (presently manual). The analysis basically consists of data quality checking and comparison of linear and non-linear machine test parameters to pre-determined baseline data. After this initial automated analysis is complete the operator's screen will show a machine performance status in the form of red light/green lights. If any one data quality check or performance parameter gives a negative indication, the red status light will be lit. If everything checks as good, the green status light will be lit.

If an operator or analyst desires a more detailed analysis, they can simply point and click on the appropriate button on the screen to work down through a few layers of indicator lights. This path will ultimately land the analyst at screens that give time waveforms of actual data from the particular machine components that indicated the problem. Spectral analysis and electrical signature analysis plots are also available at this point. With the push of a button, the program shows the reduced parameters for the linear and non-linear analyses in the form of trend plots. The trend plots show the test parameters over time, with upper and lower allowable level bands indicated on the plots. At this time the parameter testing consists of standard bands in the frequency domain that could be used generically for several different motor applications. These bands can be watched for trends above or below preset levels, and when the trend for that band moves to "bad" condition, more detailed analysis of the data by an expert can be performed. With further programming the trends could be evaluated by the computer and use of artificial intelligence to determine the causes of failures.

The overall resulting data storage consists of the original time waveforms taken when the machine is run, but also includes the archived results of the electrical signature analysis (ESA) and non-linear parameter data that are acquired and processed by the software program and analyst (after the machine is back in service).

Figure 7 shows the main screen of the data review and trend program. After the analyst has proceeded from the main screen (Figure 5) in order to review data, he will arrive at this screen. This screen presents plots that show (from top to bottom) the raw time waveform, a Fast Fourier Transform (FFT) of that waveform, and a digitally demodulated spectrum for use with ESA analyses. Also on this screen are buttons to allow review of the ESA stored parameters in a trend plot, as well as the non-linear stored parameters in a similar trend plot. Tolerance bands are set and displayed based on baseline parameters. Presently there is the capability to append the trend data file manually, but this is preferably done automatically during the earlier data collection. Figures 8 and 9 show (respectively) the ESA data and the non-linear data trend plot screens. ESA developments are further discussed later in this document.

MAGNUM MAINTENANCE SYSTEM

RootPath

%C\MAGNUM

Configuration File

config970318.txt

Calibration Data File

calibra.txt

Trend Data Labels File

trend.txt

COLLECT DATA

ANALYZE DATA

QUIT

Analysis Calling Program

Data file path

c:\magnum\esa201\esa201_970910_0829.bin

Passed File Path

c:\magnum\esa201\esa201_970910_0829.bin

Calibration Data File

calibra.txt

Units name:

Amp

Data Quality

Analysis Check

yes ☐ run minimized? (F)

no ☐

command to execute

c:\magnum\hively\dat_chck.bat

Figure 5 View of the main program front screen (top) and analysis screen (bottom).

Figure 6 Software architecture block diagram.

Figure 7 Screen display for the Magnum data review and trend program.

Figure 8 Screen display for the Magnum ESA data trending program.

Chaos Analysis

Chaos is apparently random behavior arising from nonlinear elements in deterministic systems. Chaos abounds in natural and engineering processes, and can be a dominant factor in their behavior. A key feature of chaos is extreme sensitivity to small perturbations. This trait makes long-term prediction impossible, but allows short-term control by exploiting the nonlinear sensitivity to small changes. Our ORNL team uses nonlinear methods to diagnose, predict, and control nonlinear and chaotic processes. We rely on innovative applications of theory to noisy data with limited precision. Applications of these nonlinear technologies to the Magnum CRADA effort [1-10] are described below, focusing on nonlinear analysis of machining data.

We analyzed cutting dynamics of stainless steel in the non-chatter and chatter regimes [1], toward the ultimate objective of chatter control. We used linear methods (principal components analysis, Fourier power spectra) and nonlinear techniques (mutual information function, correlation dimension and entropy spectra, Poincaré sections, return maps). We sampled three accelerations (A) at various spindle speeds: x in the cutting direction (A_x), y along the depth of cut (A_y), and z in the feed direction (A_z). The correlation dimension is typically <4 on the embedded attractor above the noise floor. Non-chatter dynamics exist at low spindle speed, with low periodicity, low acceleration amplitude, and strong chaotic features. Chatter occurs at high spindle speed, with high acceleration amplitude, weak chaotic features, and strong period-1 motion. Period-1 and -2 dynamics dominate in the x and z directions, respectively. Poincaré sections for $A_y = 0$ are sensitive to the non-chatter-to-chatter transition, which involves a change from chaotic behavior to period-1 motion along the tool axis. Return maps and Poincaré sections show the non-chatter-to-chatter transition before detection by an experienced operator, and may serve as predictors of this transition. Our work also suggests some likely alternatives for chatter control [10]. We submitted an invention disclosure [2] on these findings. Lockheed Martin Energy Research Corporation has elected to retain the commercial rights to this intellectual property.

Initial Magnum CRADA team meetings identified the need for a conceptual plan for diagnostics and control. A draft plan [3] included the following elements:

- why: closed-loop, open-architecture diagnosis and control for preventive maintenance;
- what: monitor critical Magnum components;
- where: various key locations on the Magnum;
- how: electrical-signature and chaotic-time-series analysis of Magnum parameters.

The draft plan also identified specific Magnum components to monitor and particular measurement data to analyze.

Nonlinear analysis of Magnum motor current [4] was performed on four datasets while the spindle was running idle (cutting air). The principle peaks in the Fourier spectrum were at 68.4, 87.9, 107.4, and 127.0 Hz for cutting speeds of 3000, 4000, 5000, and 6000 RPM, respectively. The first minimum (M_1) in the mutual information function provides a time scale for maximum nonlinear decorrelation, and ranged from 0.25 to 0.33 milliseconds at 3000 and 6000 RPM, respectively. The dimensionality of the dynamics was on the order of 3 at 3000-4000 RPM, rising to 4-5 at 5000-6000 RPM. This result implies more dynamical complexity at higher spindle speeds. Principle components analysis shows clear structure in the spindle motion, with the

variability amplitude decreasing with increasing spindle speed.

Nonlinear analysis of Magnum accelerometer data [5] was performed on three datasets, each with four channels (three on the gearbox and one on the spindle) while cutting air at 1000 RPM. The Fourier spectra were very similar among the three datasets, but very dissimilar among the different channels. The nonlinear decorrelation time, as measured by M_1 , ranged from 0.15 - 0.48 milliseconds. Dimensionality ranged from 6-7 for small scale dynamical changes to unity over global scale variations.

Subsequent work [6] analyzed motor current and acceleration data from the spindle while cutting air at 1800 and 10,000 RPM, and also motor current from the Z-axis while moving at 200 inches per minute. The spindle motor current data showed a sinusoidal signal at 220 Hz, plus additional chaotic dynamics. We used a patented zero-phase quadratic filter to remove the sinusoidal artifact, while preserving the nonlinear amplitude and phase relationships. The nonlinear features of the artifact-filtered data had strongly chaotic features as measured by mutual information, correlation dimension, principle components analysis, and Kolmogorov entropy. Strongly chaotic features also occurred in the spindle acceleration data. The Z-axis motor current data was consistent with pulse-width-modulated signals.

We performed extensive analysis on 38 datasets of spindle motor current for air-cutting and metal-cutting conditions [7]. We removed the 220 Hz sinusoidal artifact via the zero-phase quadratic filter, as before, leaving an irregular signal from the chaotic dynamics. Nonlinear measures of these artifact-filtered data were consistent between the first, middle, and last third of the cutting and non-cutting datasets, and were also consistent between datasets for the same operating conditions. However, Fourier spectra were very different within a single dataset, and between datasets for the same operating conditions. This second result indicates strong nonlinearity in the dynamics, which cannot be captured by linear methods. We compared air-cutting data from the old CMI spindle assembly, with the new spindle assembly at speeds of 1800 and 10,000 RPM. The nonlinear measures (correlation dimension, entropy, and mutual information) were different by >3 standard deviations at both cutting speeds. Thus, these nonlinear measures can distinguish dynamics for the old and new spindle assemblies. These same measures clearly distinguish between HSS drilling with 0.25" and 0.375" diameter bits, but cannot distinguish among drilling with new-design reground BRS, damaged new-design BRS, and worn old-design BRS bits. The latter result motivated use of a patent-pending technique [8-9] which represents the dynamics in a phase space (PS) form, which is then converted to a probability density function (PDF). An assessment compares a basecase PS-PDF to an unknown PS-PDF via a chi-squared (statistical) measure. This method distinguished different drilling conditions (reground bit, worn bit, damaged bit, and old design bit) and successive cuts with the same drill bit.

The bellows coupling on the Z-axis of the Magnum broke in the middle of July 1997. We subsequently analyzed motor current data from the weekly preventive maintenance tests from April through October 1997, for indications of this failure. We used the first dataset from 5/14/97 as the basecase, which we compared via the PS-PDF technique to later data. We found clear predictors of the failure, beginning on July 7 and continuing on July 10. The indicators returned to the normal range on August 4 after repair of the bellows coupling. Details of these results were presented to Paul McCalmont (CMI) at the 10/22/97 CRADA meeting.

We devoted substantial software development effort to implementation of the nonlinear analysis as a component of the ORNL-developed Magnum analysis package. Stand-alone research-class FORTRAN techniques had been combined previously into a patent-pending, integrated algorithm for expert-analyst use [9]. One task involved development of a data quality checking algorithm, because data of inadequate quality is unsuitable for subsequent nonlinear analysis. A second task involved development of a compact version of the PS-PDF algorithm. This CRADA effort customized the integrated algorithm, which previously ran on a 166 MHz DEC/alpha workstation, to a form that ran on a 133 MHz Pentium PC.

Electrical Signature Analysis (ESA)

ESA techniques were initially investigated on the Magnum several years ago and were shown to be effective at exposing numerous machine performance and condition indicators. This assessment was documented in a report [11] that includes typical time waveforms and frequency spectra derived from raw and demodulated motor current signals. ESA techniques have been developed by ORNL over years of research on a variety of projects. A brief history of ESA developments is indicated below.

In 1985, the Oak Ridge National Laboratory (ORNL) began a comprehensive aging assessment of motor-operated valves (MOVs) at the request of the U. S. Nuclear Regulatory Commission. A major objective of this study was to identify methods of monitoring the aging and service wear of MOVs so that maintenance could be performed prior to their failure. In addition to evaluating the diagnostic information provided by several MOV-mounted sensors, considerable efforts were made to extract useful information from the motor's running current since it could be acquired remotely (e.g., at the motor control center) and nonintrusively (using a clamp-on current sensor) [12].

MOV motor current research led to the development of several signal conditioning and signature analysis methods that exploit the intrinsic ability of an electric motor to act as a transducer. These methods provide an improved means of detecting time-dependent load and speed variations generated anywhere within the MOV and converting them into revealing "signatures" that can be used to detect degradation and incipient failures [13]. These motor current signature analysis (MCSA) techniques [14] were found to be applicable to a wide variety of motor driven equipment and have provided the foundation on which additional signal conditioning and analysis tools have been developed by ORNL in the area of electrical current, voltage and power monitoring. These developments are applicable to both motors and generators, and have now been grouped under the name electrical signature analysis (ESA). ESA technologies have now been successfully demonstrated by ORNL on a large variety of consumer and industrial equipment such as air compressors, water pumps [15], residential air conditioning units and heat pumps [16], large chillers, fans of various types and designs, automobile alternators and helicopter and aircraft generators [17,18], home appliances and tools, and other devices [19].

ESA techniques have thus far been applied most often to motor-driven machinery. Motor current signals can be obtained anywhere along the electrical line supplying power to the motor-driven device. By utilizing a clamp-on current probe to acquire raw motor current signals, no electrical

connections need to be made or broken, thus, equipment operation is not interrupted and shock hazard is minimal. Signal conditioning electronics can improve the useful dynamic range of the recorded data. For example, amplitude demodulation provides an efficient method of revealing small perturbations in the current signal by treating the dominant power line frequency component as a carrier for the machine-induced modulations. These modulations can often be hard to detect in the raw signal due to their small size; however, once demodulated and amplified, the conditioned motor current signal can be easily recorded and analyzed by a variety of techniques.

Two general MCSA techniques are now described, using a MOV as an example. In order to provide the reader adequate information to understand the MOV signatures, a brief MOV description is included.

A typical motor-operated gate valve (see Figure 10) includes a motor operator capable of providing sufficient torque that, when applied to the stem threads of a rising stem valve, delivers enough stem thrust to open and close the valve. Forces opposing stem travel can include stem packing friction, stem ejection force due to internal fluid pressure, and gate-to-guide friction induced by high fluid flow.

In a typical motor operator, the drive sleeve (containing the stem nut that mates with the valve stem) is driven by the worm gear through lug-to-lug contact. In this way, the motor can start in a relatively unloaded condition and can reach full speed before the worm gear and the drive sleeve engage. The transient running load that occurs at this engagement is referred to as the "hammerblow" and can usually be detected in a simple time waveform of the RMS motor current signal. Figure 11 shows a motor current time waveform acquired during the beginning of an opening stroke for an 18-in gate valve. In addition to the hammerblow, an increase in running current is observed as a result of friction between the valve stem and the stem packing rings when the stem begins to move.

Figure 10 Cutaway view of a typical motor-operated valve (MOV).

Figure 11 The initial 3.5 seconds of a MOV motor current time waveform showing the detection of several transient loads occurring in the motor operator and valve.

Both the amplitudes and the times of occurrences of these features provide useful condition indicators that may be trended over time. For example, the time differential between the hammerblow and initial stem movement generally reflects the clearance between the stem nut and stem thread surfaces. Likewise, the time between initial stem movement and gate unseating largely reflects the clearance between the gate and stem coupling surfaces. A precise measure of these times can provide an early indication of wear in these regions.

Figure 12 illustrates a typical frequency spectrum for an amplitude demodulated MOV motor current signal. One prominent component in the spectrum is the worm gear tooth meshing (WGTM) frequency. The existence of a spectral component at this frequency indicates that a significant motor load is associated with the meshing of the worm and worm gear. In addition to the fundamental WGTM frequency, its second harmonic ($2 \times \text{WGTM}$) is observed and worm gear rotational sidebands are seen around the WGTM peak, providing further MOV condition indication related to the worm gear drive.

By using a selective waveform inspection method (SWIM), the WGTM can be further analyzed as shown in Figure 13. In this SWIM signature, the repetitive modulating pattern consisting of 34 shorter period events represents the individual tooth meshings between the worm and 34-tooth worm gear. Studies of MOVs on test stands have confirmed that this WGTM profile is nearly constant (very little amplitude modulations) for a new MOV, but varies widely for MOVs that have seen service wear.

Figure 12 Frequency spectrum for typical MOV motor current signal

Figure 13 Application of SWIM (selective waveform inspection method) to the demodulated motor current signal from a MOV whose worm gear has 34 teeth.

Inventions

ERID #0001C on "Machine Tool Chatter Detection" was filed on 1/24/96 and elected for patenting by LMER on 3/20/96, with no subsequent action. All of the ideas in this disclosure were developed under the CMI CRADA funding.

ERID #0290 on "Nonlinear Method for Diagnosing Condition Changes" was filed on 11/14/96, for which LMER filed a patent application, "Integrated Method for Chaotic Time Series Analysis" (docket #0264 dated 5/97), and for which the US Patent Office has allowed all claims in a 4/98 office action. We are awaiting formal issue of the patent, with no date yet set by the USPO. The data quality checker was the only IP in this patent that was developed under the CMI CRADA funding.

Commercialization Possibilities

This type of PM system has high potential for commercialization. Additional work is needed to make both the software and the hardware more robust before it can be placed on the shop floor.

Plans for Future Collaboration

Cincinnati Milacron and Oak Ridge plan on doing joint predictive maintenance work in the future.

Conclusions

The skills gained and technology developed on this CRADA will be a valuable addition to the database of Y-12 knowledge needed to operate a smaller, more efficient manufacturing facility in the future. The gage nest test introduced to the maintenance organization, and the LabView software developed for spindle testing will be available for use.

Interest in predictive maintenance for machine tools and the entire manufacturing facility is growing. This growth is happening among many of the Y-12 operating organizations as well as across the entire DOE complex. At Y-12 alone, there are three projects being proposed to develop PM systems based on the groundwork done in the CRADA. One of the three proposals will involve other DOE sites.

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