Proceedings of MSEC2006
2006 ASME International Conference on Manufacturing Science and Engineering
October 8-11, 2006, Ypsilanti, MI

MSEC2006-21093

AN ADVANCED VIBRATION BASED REAL-TIME MACHINE HEALTH AND PROCESS MONITORING SYSTEM

Chandra Jalluri, Prashanth Magadi,
Mohan Viswanathan, Richard Furness
Advanced Manufacturing Technology Development,
Ford Motor Company, Dearborn, MI 48101, USA

Werner Kluft, Friedhelm Hostettler
PROMETEC GmbH,
D-52070 Aachen, Germany

ABSTRACT

The ever-increasing emphasis on product quality with increased productivity has been driving the automotive manufacturing industry to find new ways to produce high quality products without increasing production time and manufacturing costs. In addition, automotive manufacturing plants are implementing flexible manufacturing strategies with computer numerical control (CNC) machining centers to address excess capacity, shifting consumer trends and future volume uncertainty of products. Over time, plants have used several preventative and predictive maintenance methods to address machine reliability. Such systems include, but are not limited to, scheduling machine down times at regular intervals to check/replace bearings and other spindle/slide components before they can have an adverse affect on part quality. However, most of these methods and traditional systems are not cost effective and cause significant machine down-times, safety concerns and labor overheads and do not reliably monitor other process issues, such as, clamping, incoming stock variations and thermal phenomena.

This paper describes an advanced real-time vibration based machine health and process monitoring system that has been developed to address the above issues. The system, called Condition Indicator Analysis Box for CNC (CIAB™-CNC), is easily configurable, and provides real-time data and historical trends of machines, processes and tooling, enabling manufacturing plants to make accurate predictions regarding future production runs. The system also aids in the optimization of preventative maintenance tasks in a cost effective manner.

The developed system monitors machine spindle and slide for unbalance, misalignment, damaged/spalled bearings, mechanical looseness, and ball screw issues. Additionally, it performs in-process monitoring during machining as well as non-machining by individual tool and/or feature to detect tool breakages, quality issues and other gross process or machine anomalies. Innovative statistical trending algorithms enable the system to automatically adapt to valid process/parameter changes and significantly reduce the chances of false alarms and warnings. The developed system provides manufacturing plants with a tool to analyze machine tools and their associated components in an effort to gather information they can use effectively to make decisions regarding flexible machines, processes and tooling.

INTRODUCTION

Automotive manufacturing plants are increasingly moving towards flexible/agile manufacturing systems consisting of multi-tool CNC machining centers operating at high speeds and with varying process parameters. Spindles and slides are critical components of CNC machines and their performance directly contributes to the up-time and reliability of the machining processes. Additionally, spindle and slide failures are not only key contributors to machine downtime in production, but also have a great impact on part quality.

A common approach for machinery maintenance is through periodic preventative maintenance. During preventative maintenance, machines are checked (at a pre-determined frequency) for worn-out components on the spindle, slide and other critical components. However, it is not easy to determine the optimum frequency for scheduling maintenance. Additionally, it is a time and labor intensive process that causes significant production down-times.

Another approach used by manufacturing plants is predictive maintenance. Vibration monitoring of the spindle and other rotating components is the most widely used predictive maintenance technology. However, as in the previous case, this is a time consuming process that involves topping the machine and manually placing sensors on or near the critical components. This also raises safety concerns for the vibration analyst. Furthermore, this approach can only be used to monitor vibrations occurring in the idle mode, thereby providing the analyst with partial data. The vibrations occurring during machining (which are more significant) are not monitored.

There is a need for a real time monitoring system that monitors spindle, slide and tools during idle as well as machining cycles on a 24/7 basis enabling accurate predictions of impending failures. The CIAB^{TM}-CNC condition monitoring system was developed to satisfy this need. It is a low cost vibration based real-time total process monitoring system that monitors machine health (spindle, slide condition, etc.) as well as process-related factors (tooling, part clamping, incoming stock variation, thermal characteristics, etc.). The system can be configured as per specific end user requirements and applied universally to all CNC machines.

BACKGROUND

Traditional monitoring systems are based on individual tool condition analysis, and are used primarily for tool breakage. However, they do not monitor other process factors, such as, clamping, incoming stock variations and thermal phenomena. Many of these systems are based on template matching and involve complicated setup parameters that require constant fine-tuning and are prone to false alarms even during minor process or material changes. Most of the traditional process monitoring systems are not designed to simultaneously monitor system, process and components. Furthermore, most of the available systems are based on inputs other than vibration, such as, torque, power, current or force from the machine drives. However, these inputs do not have reliable discrimination capability for process monitoring.

Although vibration signature analysis has been used to characterize spindles and other rotating components on the plant floor, its usage has been limited. The data is typically collected on pre-determined schedule (based on the number of machines, production schedules, available vibration analysts, etc.) and readings are only taken under idle conditions. This method has several disadvantages:

a) Manual intervention is required which causes several minutes of downtime and safety concerns;
b) Spindles are tested at only one speed but certain defects may manifest themselves and be more severe at different speeds;
c) Readings are taken infrequently, so intermittent defects may not show up during this brief snapshot;
d) Warning and alarm limits on the data are set manually and often arbitrarily;
e) Spindles/machines behave differently under load during cutting and some defects may not be present in the idle condition.

To overcome the limitations of analysis with idle vibrations, a comprehensive vibration signature analysis technique was developed for characterizing machines [1-5]. This technique involved acquiring vibration data during machining runs in addition to idle runs. The data is then analyzed in time domain and frequency domain. Discrete Fourier Transforms (DFT) calculated by Fast Fourier Transform (FFT) algorithms is used to convert the time domain signals into frequency domain [6-7]. This technique was used as a basis to initially develop a process monitoring system for transfer-line machines. The system described in this paper is an extension of the transfer-line system to include CNC machining centers with multiple tools and part programs.

METHODOLOGY

The developed system consists of an accelerometer mounted on the machine spindle and connected to a monitoring unit which is interfaced with the machine program logic controller (PLC). The monitoring unit receives vibration data acquired by the accelerometer as well as signals related to machine events from the machine PLC. Figure 1 shows the functional architecture of the system and a brief description is given below.

The monitoring unit communicates with the machine PLC and starts recording vibration data from the accelerometer when it receives the start of cycle (SOC) signal. The monitoring unit constantly interacts with the machine PLC during the cycle and splits the cycles into machining/cutting events and non-machining/non-cutting events. Machining events are described as those when the tool is in contact with the work-piece. The non-machining events include tool changes, spindle movement from one feature to another and other events during the cycle when the tool is not in contact with the work-piece.

Two types of data are calculated and archived for all machining and non-machining events – historical trends and machining cycle time profiles. The historical trend data records one data point per parameter per tool or feature (based on the setup as uploaded through the setup file) every machining cycle. Several parameters (Root Mean Square (RMS), Kurtosis, etc.) are calculated from the raw vibration data acquired from the accelerometer. In addition, the last ten complete cycle profiles in the time domain are saved at all times. A warning or alarm is raised if any limits are violated. The alarm strategy is described later in this section. A "cycle detect" LED turns on at SOC to provide a visual cue and remains on until the end of the cycle. A red "alarm" LED turns on in case of an alarm and remains on as long as the conditions causing the alarm are present.

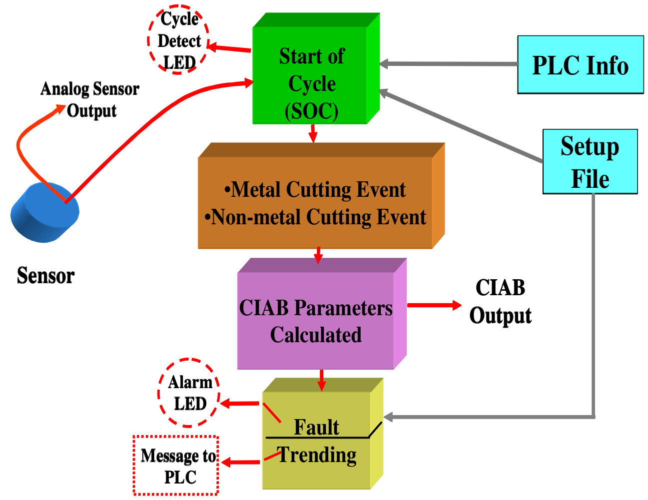


Figure 1: Functional architecture of the CIAB™-CNC system.

The developed system provides the capability to automate spindle and slide health monitoring (at user defined frequency). The spindle is monitored during idle runs to check for unbalance, misalignment, damaged bearings, and mechanical looseness issues. For the spindle monitoring programs, data is saved in both the time domain as well as frequency domain. Additionally, the transient vibrations during rapid slide movements are analyzed to detect issues with slide components such as, ball screws and linear motor drives. Furthermore, the system continuously monitors the overall vibration levels to protect the machine against any impending crashes.

Statistical algorithms are applied to set alarm and warning limits that can easily adapt to valid process and/or parameter changes. The system is capable of running in passive or active mode. When running in passive mode, the system just logs all events including alarm and warning messages, but sends no messages to the machine PLC. However, in active mode, an alarm message will be sent to the machine PLC causing the machine to stop.

In the active mode, the system can be set to stop the machine immediately upon receiving an alarm, stop the machine during the next tool change event or stop the machine at the end of the current machining cycle. Additionally, the number of limit violations that should trigger an alarm for each alarm parameter can be set and uploaded into the monitoring unit [8]. Figure 2a shows an example where the alarm trigger threshold is set as 5 out of 10 cycles. In this case, an alarm will be raised 5 limit violations are recorded within the previous 10 cycles. This enables the plant personnel to set different threshold limits for different operations. As an example, a very critical operation could have a 1 out of 1 threshold, while a non-critical or light machining operation could have a larger threshold. Figure 2b shows an example when the alarm conditions are not met.

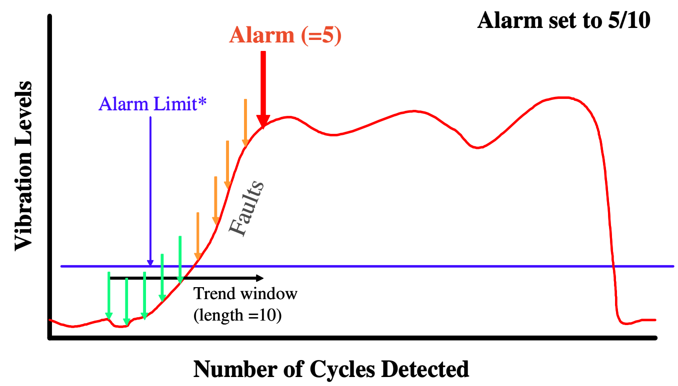


Figure 2a: An example of the alarm condition being met [8].

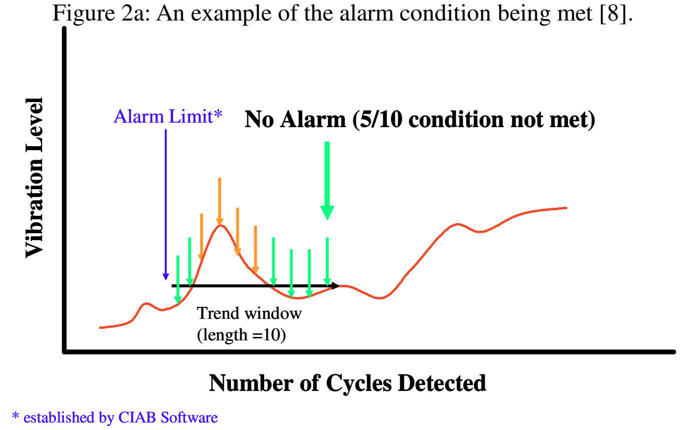
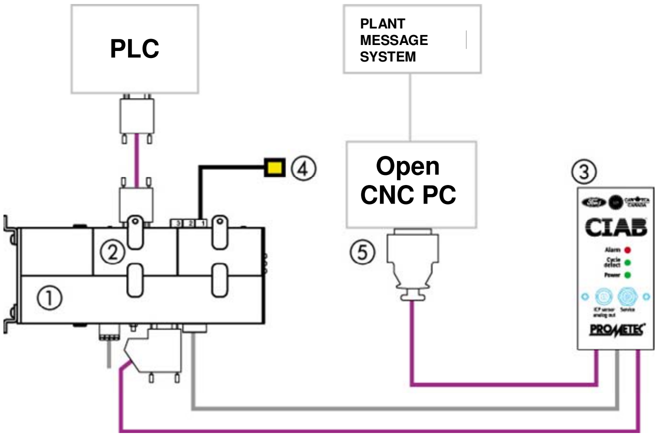


Figure 2b: An example of the alarm condition not being met.

SYSTEM HARDWARE

The hardware schematic of the system is shown in Figure 3. An accelerometer installed on the machine spindle housing acquires vibration signals that are recorded by a monitoring/ processing unit installed in the machine electrical switch cabinet. The monitoring unit communicates to the machine PLC through the Field-bus. The monitoring unit is also connected to a communication plate, which offers basic status information with three LED indicators. The communication plate is mounted outside of the machine panel. The communication plate in turn communicates with the machine PC and sends the information to the Operator Screen Software which is installed on the Machine PC and accessible through the human machine interface (HMI). The communication plate also includes an analog accelerometer output connection (for acquiring raw vibration signals) and a service connection for the temporary connection of a laptop to collect data from the monitoring unit. Multiple monitoring units can operate independently of one another and can be assigned to different machining stations.

The monitoring unit is equipped with a 16-bit microcontroller board with 1 MB of S-RAM memory, which collects the data to save cycle time profiles on a 128 MB solid state flash card. The microcontroller is capable of generating extensive trending values and is responsible for the data communication to machine, HMI, laptop and the plant network information system.



Legend:
(1) Monitoring/ Processing Unit
(2) Machine Interface Bus Module
(3) Communication Plate with Service Socket and Analog Output
(4) ICP Accelerometer
(5) Connection to CNC-PC and/or Laptop/PC

Figure 3: Hardware Schematic of the developed System.

Additionally, the monitoring unit carries a Digital Signal Processor (DSP) with 8 MB of fast SD-RAM memory enabling the system to carry out real-time calculations, such as, Fast Fourier Transforms (FFT), Root Mean Square (RMS), Kurtosis and other statistical calculations.

SYSTEM SOFTWARE

The machine PLC interface is the first level of communication. Upon generation of a fault, the message is sent by the monitoring system to the machine PLC. Based on the type of fault and the configuration, the machine PLC responds by stopping the machine and also sending the message to plant floor messaging systems.

The second level of communication is the Operator Screen software installed on the machine PC and accessible through the HMI. This allows the machine operators and other plant personnel to check the system status, trend charts and other relevant data on the machine PC screen. Figure 4 shows the screenshot main status screen of the Operator Screens software that shows the overall status of the system. Detailed views can be accessed by selecting the options at the bottom of the main status screen. Figure 4 shows an example where the status screen displays an alarm. The details of the alarm, such as, the tool causing the alarm, parameter, type of fault, and other details are provided under the "Alarm Details" section of the main status screen.

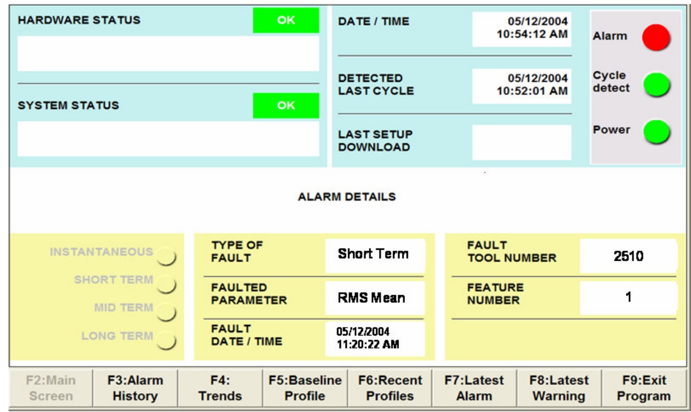


Figure 4: Main status screen of the Operator Screen Software as displayed on the HMI.

The third level of communication is the Utility software, which is a client application running on a laptop or desktop PC. The Utility software allows the user to connect to a monitoring unit for setup and data download. Data for all available parameters can be downloaded from the unit into the laptop. Data can be archived in a database for detailed analysis. Figure 5 shows a typical historical trend chart for a selected parameter (RMS in this example) of a tool. The "saw-tooth" pattern is typical of most tools and reflects tool changes. The vibration levels are low when the tool is new, and gradually increase until they break or are changed. Figure 6 shows a typical time profile for one machining cycle. The top chart shows the complete cycle profile, the middle chart shows the profile for the selected tool (indicated by the shaded area in the top chart), and the bottom chart shows the profile for features of the selected tool (indicated by the two shaded areas in the middle chart). The tool selected in this example machines two features.

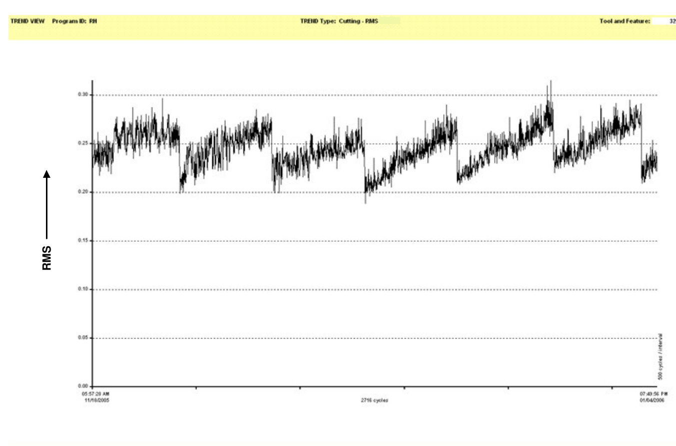


Figure 5: A typical trend chart screen of the client application (Utility) software showing historical data.

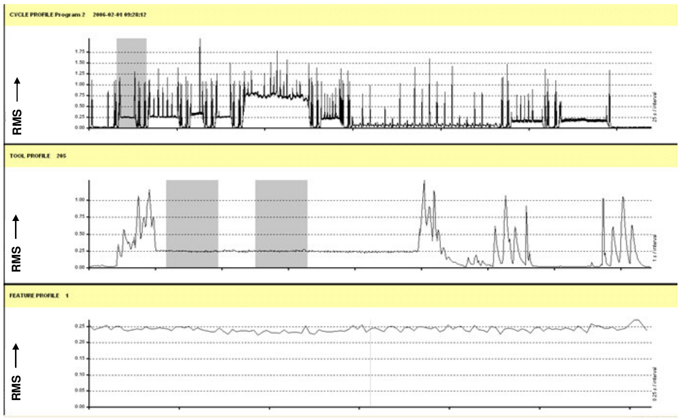


Figure 6: A typical cycle time profile screen of the client application (Utility) software.

CASE STUDIES

Several pilot test systems were first installed and tested over a period of two years. The data and results acquired were used in the development of algorithms for alarm and warning strategy. In addition, further enhancements were made to make the system reliable and robust.

One significant finding during the study was the detection of significant under-design on a prototype machine. It was found that the spindle mounting and machine structure had a natural frequency of about 250 Hz in the machine (in the X-axis direction); causing resonance at operating speeds above 13000 RPM (refer to the left side of the trend in Figure 7). Furthermore, spindle/tooling stiffness values were generally low and significantly low in horizontal direction (or X-axis). This was evidenced during idle runs (detection of resonance), transmissivity (detection of higher vibrations during horizontal traverse), machining runs and stiffness tests.

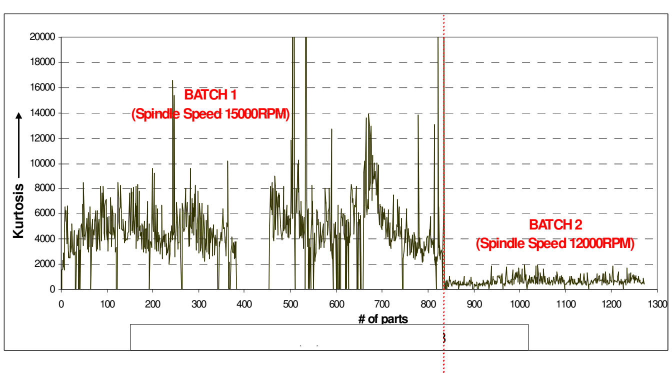


Figure 7: A trend screen showing significant reduction in vibration levels after modification of the machine structure.

Based on this data, it was recommended to increase the spindle mounting/machine structure stiffness to eliminate the resonance condition within the operating range of the spindle and improve spindle life and part quality. Additional follow-up tests conducted by the machine manufacturer confirmed the spindle mounting/ structure design issues. Several design changes were incorporated after which the vibration levels reduced significantly (refer to the right side of the trend in Figure 7).

On another occasion, it was noticed that the spindle on one of the pilot machines was experiencing severe vibrations during the withdrawal of a drill after drilling a hole. Figure 8 shows an example of a normal (top) and a high vibration (bottom) drill cycle profile. The ovals indicate the portion of the cycle when the drill withdraws from the hole.

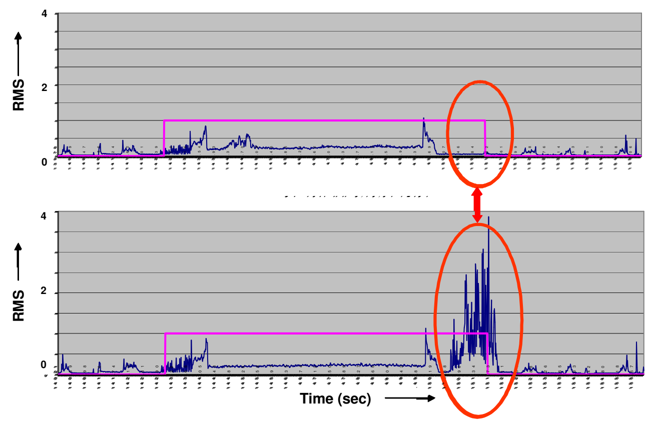


Figure 8: A profile screen showing an example of a good cycle (top) and a noisy cycle (bottom).

A detailed analysis of the historical trend and profile data of the indicated the Z-axis slide as the source of high vibrations. Slide analysis test data indicated the Z-axis slide vibrations to be significantly higher when compared to other similar machines. The root cause was identified as the ball screw on the Z-Axis slide, which had lost pre-load and was causing severe vibration during Z-axis traverse of the slide.

Slide Analysis involves monitoring and checking transient vibrations during rapid slide movements. After the replacement of the ball screw, the process returned within control and there were no further tool breakages (as opposed to 70 tool breakages noted on that machine before the replacement). Figure 9 shows historical trend for the drill before (left portion) and after (right portion) the replacement of the Z-axis slide ball screw.

BENEFITS AND IMPACT

The developed system can be utilized in large scale CNC flexible modules as a production stability monitor to provide the following benefits:

a) Protective umbrella against catastrophic failures
b) Increased process and machine reliability

c) Reduced safety risks and downtime associated with traditional spindle preventative maintenance.
d) Continuous monitoring of spindles will in turn improve spindle and tool life
e) Providing Reliability and Maintainability (R & M) support data.

In addition, the developed system will provide a better understanding of machining processes. Enhanced performance of machines will improve part quality as well as noise, vibration and harshness (NVH) characteristics by providing more control over critical machining processes.

One significant of this system is the automated monitoring of machine spindle and slides. Data is trended and archived automatically enabling Vibration Analysts and plant personnel to perform detailed analysis and follow up, resulting in significant time and cost savings due to reduced downtime and safety risks to the plant personnel.

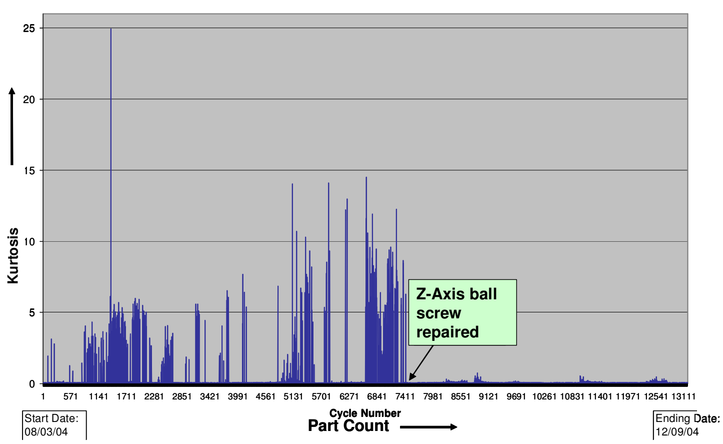


Figure 9: A trend screen showing vibration levels before (left side) and after (right side) improvement.

SUMMARY AND CONCLUSION

The ever-increasing emphasis on product quality continues to put pressure on all automotive plants to find new ways to produce high quality products without increasing production time or otherwise increasing manufacturing costs. Inherent in this high quality-low cost dichotomy is a need to reduce scrap while obtaining the longest possible life from manufacturing tools and equipment. Thus, while increasing the number of tooling changes and/or decreasing the time between machine tool maintenance may increase product quality, it will also result in an unnecessary increase in tooling costs and/or lost production time. The developed system provides manufacturing plants with a unique tool to optimize tool, slide and spindle life. Furthermore, the developed system aids in continuous process improvement and helps the plants lower costs while simultaneously improving quality.

REFERENCES

[1] Seth, B. B. and Hamidieh, Y. A., "Machine Condition Signature Analysis for Reliability and Maintainability Improvement," Proceedings of International Programmable Controller's Conference, Detroit, MI, 1993.

[2] Seth, B. B. and Hamidieh, Y. A., "System and Method for Machining Process Characterization using Mechanical Signature Analysis," United States Patent No. 5663894, 1997.

[3] Seth, B. B., Hamidieh, Y. A. and Jalluri, C., "A Methodology for Machining Process Characterization," Society of Automotive Engineers, No. 961636, 1996.

[4] Braun, S. G. and Seth, B. B., "Analysis of Repetitive Mechanical Signatures," Journal of Sound and Vibration, Vol. 70, No. 4, 1980.

[5] Seth, B. B., Hamidieh, Y. A., Tata, B., Tonello, E. T., Lau, K. C. and Ma, Q., "Geometric and Thermal Characterization of a Machining Center under Dry and Wet Conditions," Society of Automotive Engineers, No. 961640, 1996.

[6] Barron, R., "Engineering Condition Monitoring – Practice, Methods and Applications," ISBN 0-582-24656-3, Addison Wesley Longman, New York, NY, 1996.

[7] Wowk, V., "Machinery Vibration: Measurement and Analysis," ISBN 0-07-071936-5, McGraw-Hill, New York, NY, 1991.

[8] Edie, P. C., Simpson, R. A. and Kaufman, I. G., "System and Method for Machining Data Management," United States Patent No. 6845340, 2005.