Update of Process Monitoring and Control Research at NC State University

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15th International Wood Machining Seminar  
July 30 – August 1, 2001  
Pages 511 - 522
Abstract

This paper is an overview of the research being conducted at the North Carolina State University’s Wood Machining and Tooling Research Program (WMTRP) in the area of process monitoring and control. The objective is to increase productivity, usable “tool life”, and product quality while reducing unscheduled down time. The high price of labor and raw material coupled with the increase in production speeds can make unacceptable product going undetected a costly mistake. Research at the WMTRP has dealt with equipping a CNC router or belt sander with sensors that can alert the operator when the “cutting tool” is nearing the end of it’s usable life or when the quality of the workpiece has degraded below acceptable limits.

The research has proceeded in three distinct directions. The first is monitoring tool wear on a CNC router. Work to date has shown that an accelerometer mounted on the spindle can be used not only to alert an operator that the tool is becoming worn but can also be used as input for a closed loop system that can control the spindle speed to maintain product quality as the tool wears. The second area of research is monitoring abrasive machining with similar sensors as investigated for the router. In this research, an accelerometer mounted on the spindle gives information when the abrasive is beginning to wear. Another sensor type, which shows promise, is a vision system that gives information about the loading of the abrasive. The advantage of this type of sensor is that it can also be used on multiple head, wide belt sanders which are more difficult to instrument with accelerometers. Output from these sensors can alert the operator that a belt is worn or loaded. Research is underway to develop a closed-loop control strategy based on the input from the sensor(s). The third area of research is the monitoring of the resultant surface quality after a machining operation. Research has shown that this type of sensor can detect surface “defects” caused by various problems in the machining operation such as tool/spindle unbalance, dull tooling, un-jointed tooling, and grit size. Research has shown that this type of sensor can provide valuable information to the operator on the condition of the machining operation or the raw material itself.

Following will be a discussion of each of these areas of research.
Introduction

The need to maintain high product quality while improving production rates has driven the wood products industry to automate many machining operations. Increases in labor and raw material costs have also provided the incentive to increase production throughput as well as reduce the number and technical skill levels of the required workforce. A disadvantage of this trend is that a change in the condition of the machining process or the resultant quality of the workpiece can go undetected for a substantial period of time causing significant impact on the economics of the machining operation. Substantial research has been conducted in developing remote sensing strategies to aid machine operators in detecting unwanted machining conditions or assisting in maintaining proper machining parameters regardless of the condition of the cutting tool.

Research in the area of process monitoring and control at the WMTRP has included determining the “best” sensor for monitoring a router operation as well as various abrasive machining operations. The research on the router has been limited to melamine-coated particleboard. This was because this type of product is sensitive to the melamine chipping as the blade becomes dull. Often times the determination when a cutting tool is dull is a rather ambiguous threshold that differs from manufacturer to manufacturer. This research included monitoring cutting power, acoustic emission, sound, and spindle vibration. Research on process monitoring of abrasive processes has included both belt sanding and peripheral sanding on a CNC machine center. This research was conducted on various hardwoods and softwoods. Research in this area has included evaluating various types of sensors including an acoustic emission sensor, a spindle mounted accelerometer, a vision system, a color contrast detector and a power meter.

Research on using surface quality monitoring as a process monitoring tool has also been investigated. The sensor used was an optical profilometer. The system has been investigated on moulders, wide belt sanders, saws, and routers. Workpiece materials that have been investigated include various hardwoods, softwoods, particleboard, and MDF. This system has been used to detect tool wear, machining/tool vibration, tool jointing, and size and type of abrasive grit.

Background

Router

Process monitoring or tool condition monitoring for peripheral milling machines has been the topic of much research. A limited amount of research has been directed toward woodworking. Most of the disadvantages of various sensing technologies investigated for the metal cutting industry also apply for the woodworking industry. In addition, the increased cutting speeds that are more common in many woodcutting operations further limit the possible sensor strategies. The metal cutting industry also has machining and sensing technologies that are currently impractical for the woodworking industry due to economical reasons. The sensors that are currently used in the metal cutting industrial environments include power, force, vibration, and acoustic emission. The reader is referred to the review by Byrne et. al. (1995), Tool Condition Monitoring (TCM) – The Status of Research and Industrial Application. This
review discusses the various sensing techniques and their advantages and disadvantages. This review also discusses sensing technologies that are not normally considered practical from an industrial environment standpoint. These include direct measurement of tool wear with optical systems; direct measurement of surface quality with optical or ultrasonic position detectors; and indirect measurement of tool wear by the measurement of tool temperature, measurement of electrical resistivity between the tool and the workpiece, or the sound generated as the tool is worn using microphones. Much research, both before and after this review, has tried to make some of these indirect measurements more robust in an industrial environment.

Research in process monitoring for the woodworking industry has included work by Fujii et. al. (1993), which used a microphone and pattern recognition techniques to discriminate different stages of wear in a fixed-knife planer and a circular saw. Cyra et. al. (1996) also used input from a microphone to control feed speed of a router.

Research by Smith (1996) at the WMTRP demonstrated that power consumption was not sensitive enough for monitoring tool wear at the machining conditions that are common on a CNC router. Figure 1 shows a summary of these results. Research by Lemaster et. al. (2000, Part 1) discusses research results aimed at determining the best sensor to use to monitor tool wear and product quality (melamine chipping) when machining melamine coated particleboard on a CNC wood router. This research investigated the use of an acoustic emission (AE) sensor, an acoustic microphone, and an accelerometer mounted on the spindle housing.

![Figure 1: Overall sensitivity of power consumption to various machining parameters.](image)

Of the sensors investigated, it appeared that the spindle-mounted accelerometer was best at monitoring tool wear. The spindle vibration tends to increase up to a given magnitude and then drop off sharply. This has been correlated visually with the smooth tool wear and then edge chipping of the cutting tool. The optimum frequency range (1000 Hz – 4000 Hz) of the bandpass filter was arrived at empirically. Though this type of relationship was observed in metal cutting, a definite source of the signal has been speculated but not identified. When the carbide blade was replaced with a steel blade on the blade, the relationship was nearly linear with no fall of signal from the accelerometer being observed.
Additional work in Part 2 by Lemaster et. al. (2000) demonstrated that increasing the spindle speed for a worn tool decreased the degree of chipping of the melamine. This result was contrary to conventional wisdom of increasing the chip thickness as the tool wears for solid wood. This research showed that the effect of tool wear on the product quality could be compensated for, to some degree, by increasing the spindle speed as the blade wore. Further research showed a large variability in the “abrasiveness” of the workpiece material. This would effectively preclude the use of a strategy where the spindle speed was increased at regular time intervals instead of using input from a sensor. This work also showed that the sensor input was also affected by the speed of the spindle. Additional work presented later in this paper shows a simple strategy that was developed to take into account this increase in spindle vibration as a result of an increase in spindle speed.

**Abrasive Machining**

Work by Lemaster (1992) showed that acoustic emission (AE) was sensitive to contact area, condition of abrasive, grit size, radial and longitudinal faces of the workpiece. Lemaster and Dornfeld (1993) showed that the AE signal increased with increasing feed speed but was relatively insensitive to arbor speed. They also found that the greater the depth of cut the greater the material removal rate and the greater the acoustic emission signal. There was also a species effect on the acoustic emission signal. Lemaster and Dornfeld (1993) also found that while the AE signal was sensitive to the wear of the abrasives it was relatively insensitive to whether the abrasive was cleaned. Work by Murase et. al. (1995,1997) also showed that the AE signal increased with an increase in grit number. This was probably due to the fact that 220 grit had more contact area then a 100 grit abrasive which had fewer, larger grains. Murase et. al. also showed that when sanding perpendicular to the wood grain the AE signal was greater than when sanding parallel to the grain. This was correlated to the stock removal rates which were greater when sanding perpendicular to the grain. Their work also showed that an increase in sanding pressure resulted in an increase in AE signal. Their work, however, showed a decrease in AE while the work by Lemaster (1992) and Lemaster and Dornfeld (1993) showed an increase in AE. This could probably be explained due to the fact that the two research projects used different parameters to quantify the AE signal. The work by Lemaster use the root mean square of the AE signal (AE) whereas the work by Murase used AE count rate. The AE count rate is a threshold dependent parameter. The work by Murase showed that the number of high amplitude peaks in the AE signal decreased while the work by Lemaster showed that the energy content of the AE signal increased with an increase sanding time. This is an important observation as the two AE parameters together can provide more precise information on the AE signal. In this case, the number of lower amplitude peaks of the AE signal must increase with increasing sample time. Work by Matsumoto and Murase (1997) also showed that cleaning of the abrasives resulted in an increase stock removal rate but did not change the AE signal level.

**Surface Quality Evaluation**

Research has been also been conducted in using the resulting quality of the surface of the workpiece as a process monitoring tool. Work by Lemaster and Taylor (1999) describes a
system that uses a laser-based range finder or position sensing device to measure the changes in the height of the workpiece as it passes beneath the detector. This yields a two-dimensional surface profile that is similar to the surface profile from a standard stylus surface quality evaluation system. The work reported by Lemaster and Taylor (1999) has shown that the laser-based system can be used to detect if a moulder head is properly jointed or not. The system can also detect the degradation of the workpiece surface as the tool wears.

**Experimental Setup**

**Router**

In an effort to see if the relationships between spindle vibration and tool wear described by Lemaster et. al. (2000) could be used as a process control strategy, a series of experiments were conducted on a CNC router. The first experiment consisted of wearing the cutting tool at different spindle speeds. A micro-grain tungsten carbide insert with a 3% cobalt binder was used as the cutting tool. The workpiece material was melamine-coated particleboard. A feed speed of 9.1 m/min. (360 ipm) and a depth of cut of 1.6 mm (0.0625 in.) were used. A series of repetitive cuts were made on a Timesavers router. The total length of cut of 200 meters was conducted. The speeds used were 12,000, 15,000, and 18,000 rpm. The results showed that the faster the spindle speed the greater the tool wear.

From Lemaster et. al. (2000) it was determined that the higher the spindle speed the less chipping occurred at any degree of tool wear. The next experiment consisted of determining if increasing the spindle speed as tool wear begins to cause chipping could reduce the amount of chipping. Three cutting situations were investigated. The first (I) was when the spindle speed was set at its maximum so that edge chipping was minimized. As mentioned previously, the higher spindle speeds caused quicker tool wear. The second (II) was a simple “one-step” strategy, where the spindle speed was kept at a slow speed to reduce tool wear until chipping occurred at which time the spindle speed was increased to a maximum speed of 18,000 rpm. The type III speed control strategy was to start the spindle speed slow (12,600 rpm) and anytime chipping of the melamine was observed the spindle speed was increased by 5%. This was done until the maximum spindle speed of 18,000 rpm was reached. The machining parameters were the same as described above. Cutting was continued until chipping at 18,000 begin to occur at which time the cutting was stopped. As can be seen from figure 2, by controlling the spindle speed a nearly 20% increase in “usable tool life” was experienced. Speeding up the spindle decreased the chip load, which helped compensate for the tip of the cutting tool becoming blunt. It should also be noted that chipping occurred after only 10 meters when the spindle speed was at 9,000 rpm.
The next step in the study was to determine if the spindle speed could be adjusted automatically based on the vibration signal from the spindle mounted accelerometer. Since the vibration signal increased as the spindle speed was increased it was decided that the first three meters of cutting after a spindle speed was changed would be used as a “learning mode” to establish a base line for the vibration signal. Then it was decided that as the spindle vibration signal increased by 15% the spindle would be increased by 10%. These values were empirically set and based on numerous trial cutting passes. After the spindle speed reached its maximum of 18,000 rpm, cutting would continue until the vibration signal increased an additional 15% at which time the computer would automatically terminate cutting and alert the operator that the tooling needed changing. Though this was a very crude control strategy, the results showed greater than a doubling of the “usable tool life” of the tool whose speed was controlled by the computer. Figure 3 shows the results of the length of cut until chipping occurred on the melamine coating of the particleboard.
The work to date has demonstrated that the machining process can be monitored with the appropriate sensors and the machining parameters can be altered based on the sensor input to maintain product quality. The work to date has been on a single CNC router and spindle. Work is underway to insure that these relationships will hold true for different spindles and routers. Work is also underway to try and determine the source of the spindle vibration since the relationship between the magnitude and frequency of the vibration signal and tool wear has been empirically established.

**Abrasive Machining**

A series of preliminary tests were conducted on a CNC turret machining center (Thermwood Model 40™ turret) that has a sanding head to insure that the relationships between acoustic emission and abrasive machining parameters were similar to those reported in the literature discussed above. When the AE sensor was mounted on the workpiece, the AE sensor was sensitive to changes in the feed speed, abrasive wear etc. as discussed previously. However, preliminary work showed that results similar to those on a router, as discussed by Lemaster et. al. (Part I, 2000), the spindle mounted AE sensor was not sensitive to changes in the state of the cutting tool. This is also similar to that discussed in the review by Byrnes et. al. (1995). The spindle mounted AE sensor is too sensitive to bearing noise to detect changes in the state of the tool. Work is underway to evaluate the vibration sensor used in the router study. Since the use of sanding heads on a router has still not become a common practice, initial efforts in process monitoring of an abrasive machining process at the WMTRP has since concentrated on belt sanding as discussed below.

The use of a power sensor was tried first. A power sensor is an inexpensive device that is easy to implement. A power sensor by Load Controls was used on a standard 6 x 48 inch (152 x
1219 mm) belt sander. The power was monitored for different grit sizes, workpiece species, and sanding pressures. As reported in the literature and experienced in the router study at the WMTRP reported above, the power consumption of the process was not a good indicator of the condition of the tool (abrasives). Power could be used as an indicator if the abrasives were completely worn out but was not sensitive to small variations in the condition of the abrasives.

Since another method of monitoring the condition of the abrasive is to monitor loading of the wood fiber into the abrasive, a series of optical based experiments were designed. The experiment used two types of optical devices, a CCD camera and an optical color contrast detector (R55 Expert™ by Banner®). The contrast detector is similar to a camera except that on-board electronics determine the average gray scale intensity of the surface. This type of detector is inexpensive and eliminates the need for image analysis software as needed by the camera system. The disadvantage of this type of detector is that it has to be placed very close (10 mm) to the surface being evaluated. The surface of the abrasive was monitored with the camera, both while the belt was moving and while the belt was at rest. This was to determine if it would be possible to continuously monitor the abrasive belt.

Figure 4 shows a photograph of abrasive loading while the belt is moving. The whiter area is the part of the belt that has been sanding the wood and the darker area is untouched sandpaper. This photograph shows that the loading is not consistent over the entire width of the belt. It was reasoned that the heaviest loading would be what would govern the quality of the machining process. If only one strip of the abrasive became so loaded that workpiece burning occurred, then the value of the entire workpiece would still be affected.

The color contrast detector is capable of detecting 10 levels of contrast. The detector was calibrated with the actual workpiece being the highest intensity or level 10 and the unused abrasive being the lowest intensity level or level 1.

The remaining work will be determining appropriate threshold levels of loading to determine process control decision points.
The experiment consisted of placing a 75 mm x 100 mm piece of southern yellow pine on a standard 6 x 48 inch (152 x 1219 mm) belt sander. A weight was placed on top of the specimen to provide sanding pressure. In this case a weight to provide 0.75 psi of pressure was used. A P100 aluminum oxide belt was used for this experiment. The specimen and weight were placed on the sander for 3 minutes and then removed. The image of the belt was recorded by the camera with the belt moving and stationary. The color contrast detector was used with the belt stationary. The color contrast at the place of maximum loading was recorded. Though the image intensity from the camera can be obtained in real time, in this experiment it was obtained off-line using SigmaScan™ image analysis software. Figure 5 shows the results from the color contrast detector. As can be seen in the figure, the abrasive belt went through a series of loading and then apparent unloading. This was correlated to visual inspection of the abrasive belt during the test. The result for the video camera was similar but more variable due to changes in the lighting conditions. As with all machine vision setups, the setup and control of the lighting is one of the most critical steps.

![Figure 5: Change in color of abrasive belt as a function of sanding time: color contrast detector.](image)

**Surface Quality Assessment**

To illustrate the ability of the optical profilometer to be used as a process monitor tool, a variety of surfaces from various machining operations have been collected and scanned. In addition, the sensor was placed on the outfeed table for a variety of machining operations to insure the sensor was able to accurately monitor the surface even in the presence of machine vibration. Furthermore, frequency analysis of the resulting surface profiles from the profilometer can provide additional information on the process. Figure 6 shows the frequency plot from a surface profile obtained with the system mounted on the outfeed of a moulder. The four knife moulder head had been set up intentionally so that it was producing a single knife finish. As can be seen in the plot, a surface quality equivalent to 10 marks per 25 mm (1 inch) was produced. What is also apparent from this figure is that the optical system can operate when other machine
vibration is present. Experience to date has shown that normally the frequency of the vibration of the machine is not in the same range as the frequency of interest of the surface.

The optical system has been tested on wide belt sanders, moulders and saws. Work is continuing to help manufacturers interface with the surface quality assessment system to optimize their machining operation.

![Frequency Spectrum of Surface Height](image)

**Figure 6**: Frequency domain plot of surface profile from a 1 knife finish (10 knife marks per 25 mm) on a moulder.

**Conclusions**

This paper presents a brief overview of the process monitoring and control research being conducted at the North Carolina State University’s Wood Machining and Tooling Research Program. Work is being conducted on monitoring and controlling a CNC router so that fine adjustments can be made in the machining parameters in order to maintain product quality as the cutting tool wears. In this project an accelerometer mounted on the spindle housing measuring spindle vibration has been shown to be sensitive to changes in tool wear and edge chipping of the melamine coated particleboard.

Work in monitoring abrasive machining has included monitoring acoustic emission, power, vibration and abrasive loading. It appears that one of the more straightforward approaches is the use of an optical system that measures changes in the color contrast of the abrasive belt. This sensing technology is simple and inexpensive. A disadvantage of the color contrast detector over traditional machine vision systems is that the detector has to be very close to the surface of the abrasive. A disadvantage of the machine vision setup is the expense and degree of complexity as well as the need to precisely control the lighting.

Results was also presented of work on measuring the quality of the surface of the workpiece and using that information as input on the state of the machining process. This research used a laser based position sensing device as an optical profilometer. This system is capable of
detecting and measuring surface irregularities caused by such machining problems as machine vibration, tool unbalance, and tool wear. Furthermore, frequency analysis of the resulting surface profile can show if the surface irregularities are random or periodic in nature. This aids in the identification of the source of the machining problem.

Acknowledgements

This work was funded in part, by USDA grant no. 99-03035 through support of the Wood Machining and Tooling Research Program at North Carolina State University.

Literature Cited


