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Low-cost sensors and analytics for a digital factory

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Low-cost sensors and analytics for a digital factory

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ABSTRACT

ORNL Manufacturing Demonstration Facility and Perisense worked on a low-cost solution for machining process monitoring to enable a digital factory. Enabling machine connectivity for digital factors is expensive for many small to medium manufacturers. The hypothesis for the research project is that a low-cost sensor suite, which can be retrofitted to a legacy machine tool or a new machine tool, can effectively provide real-time, in-situ sensing for manufacturing processes, which can enable improvements in process performance and efficiency. The Perisense sensor node was installed on the Haas TM1 machine with a current sensor and an accelerometer. Cutting tests were performed at different process parameters and sensor data was recorded. Results show a correlation of the current sensor to the spindle load. The accelerometer, mounted on the machine base, showed a correlation to the spindle speed as well as the spindle load. The sensor data can be used to monitor the machining process and provide insights on the machine spindle load utilization.

1. INTRODUCTION

ORNL Manufacturing Demonstration Facility and Perisense completed the following tasks from Phase 1. The Perisense node was successfully installed on the Hass TM1 and the Makino machine. Machining experiments were conducted to identify process and machine health metrics. A power sensor and an acoustic sensor have been identified as potential additions to the Perisense sensor node. The task of developing analytics and metrics for sensor data is ongoing and will extend into Phase 2 as additional experiments are performed and data is collected. Note that the amount of testing and data collection from the Perisense node was severely limited and delayed due to the ongoing COVID-19 pandemic and the associated disruptions. A detailed description of the results from the Phase I activities are listed in the report.

2. PERISENSE NODE INSTALLATION

Two Perisense nodes were acquired and installed on the Makino A51NX and Haas TM1. Figure 1 shows the current sensors and the Perisense node installed on the Haas TM1 machine. Note that the Perisense node contains a 3-axis accelerometer and a temperature sensor. The Perisense node installation is non-invasive and can be completed in 30 minutes. One of the key challenges in the data collection from the Perisense node was the lack of a wired internet connection for the node at the MDF. As a result, a cellular MiFi unit was used to transmit the data. However, the MiFi unit is not as reliable as a wired connection resulting in intermittent data drop-offs. ORNL MDF has plans to install wired internet nodes in FY21.

The following insight was observed during the installation process. The Perisense installation document instructs to install the current sensors on the main power of the machine. The current sensor will measure the entire current draw of the machine (spindle, axis, fans, etc). However, the spindle current is directly associated with the spindle load, and machining process and is of interest for monitoring the machining process. Therefore, the two current sensors were installed on the spindle drive to measure the spindle current. The current Perisense method for sampling the data is as follows. The accelerometer sampling rate is 500 Hz. The node acquires 256 samples in the x, y, and z directions and calculates the root mean square (RMS) in each direction. The RMS value is reported on the dashboard. The two current sensors acquire 200 points at 500 Hz sampling rate to calculate the RMS. The sampling for each sensor is sequential. There is a 9 second sleep time between each RMS sample. The 9 second sleep time results in a sample approximately every 10 seconds. It was observed that the 10-second sampling rate is slow for a machining operation to detect process insights such as multiple cuts of small duration, tool changes, machine door open and close, tool breakage, and a spindle crash. To increase the sample time, the number of samples for RMS calculation for the accelerometer was reduced to 30 samples and the sleep time of 9 seconds between each sample was eliminated. This enables the sampling of each sensor sequentially in 1.2 seconds.

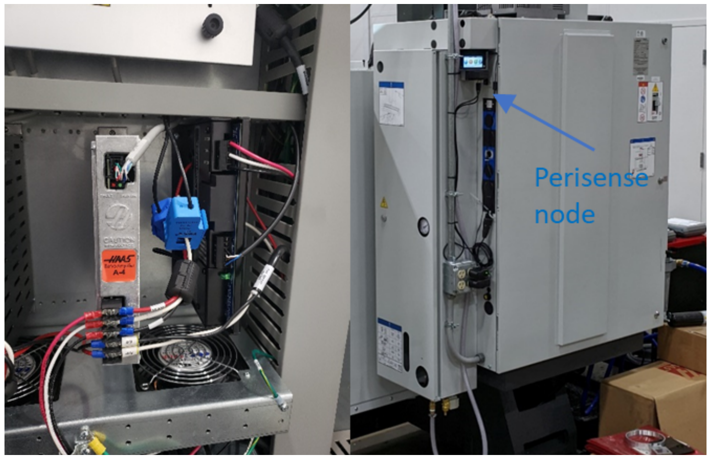

Figure 1: Installation of the Perisense sensor node on the Haas TM1 machine; the left figure shows the blue clamps for the current sensor and the right figure shows the node with the accelerometer and temperature sensor mounted on the machine cabinet.

3. PRELIMINARY DATA COLLECTION

To test the Perisense sensor node, idle spindle speed tests were performed. The spindle speed was increased from 1000 rpm to 6000 rpm with 1000 rpm increments with a dwell of 300 seconds between each increase. The test was repeated two times. Figure 2 shows a screenshot of the Perisense dashboard with the current data displayed for the two runs. Figure 3 shows the spindle current as a function of spindle speed for the two runs. As seen in Fig. 2, the spindle current can identify the spindle start. The Perisense dashboard uses a threshold value to detect spindle off (not running) and spindle on (running). The percentage of time the spindle is off is an important insight into machining process efficiency. Figure 3 shows that the spindle current reduces slightly with spindle speed. As seen from Fig. 3, similar values were obtained from both the current sensors. One current sensor can be removed in the future, thereby reducing the sampling time for each sensor to 0.6 seconds. Alternatively, the second current sensor can be installed on the machine main power and be used to measure the total energy consumption for the machine. Figure 4 shows accelerometer data for the idle spindle speed tests. In the location of the node on the machine cabinet (shown in Fig. 1), the spindle speed showed no effect on the accelerometer.

To detect the spindle start and influence of spindle speed on the accelerometer, different locations for the node were evaluated. The objective of this study was to find the optimal location for mounting the sensor node which will correlate with spindle speed. Four locations were tested where the node was mounted on the *z*-axis column at the base of the machine. The locations evaluated are shown in Figure 5; location A (top left), location B (top right), location C (bottom left), and location D (bottom right). An idle spindle speed program was run to sweep spindle speeds from 100 rpm to 6000 rpm with 100 rpm increment. The total run time of the program was 5 minutes with 5 seconds at each spindle speed. Figure 6 shows the accelerometer RMS results in *x*, *y*, and *z* directions for the four locations. As seen from Fig. 6, location A was the best showing an increase in the accelerometer values for *x* and *y* directions with spindle speed. For all the directions, *z*-direction acceleration showed no correlation with spindle speed. The idle spindle speed tests can be used to monitor the structural health of the machine. The test can be repeated periodically (for example, once every week) and the accelerometer data can be compared with a calibration test performed on a new machine. If the magnitude of the accelerometer increases over time, it can point to machine health degradation. For example, an unbalance spindle can lead to an increase in vibration under idle conditions. The spindle speed tests can be a quick check to query machine health using the accelerometer. The use of accelerometers for machine structural health monitoring will be further evaluated in Phase II.

Figure 2: Perisense dashboard with the current sensor data displayed for the two idle spindle speed tests.

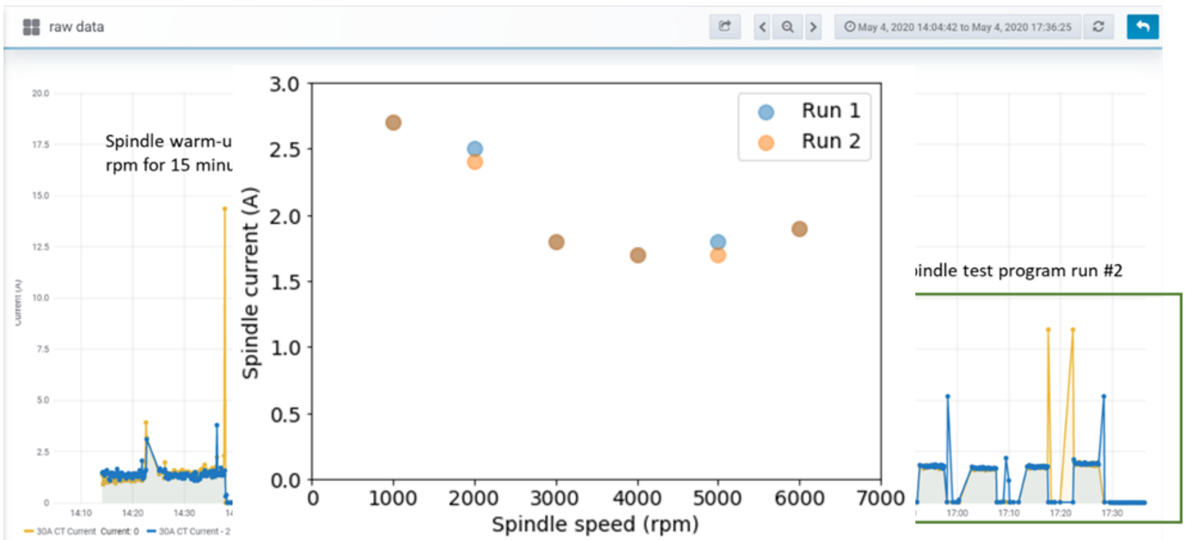

Figure 3: Spindle current as a function of spindle speed.

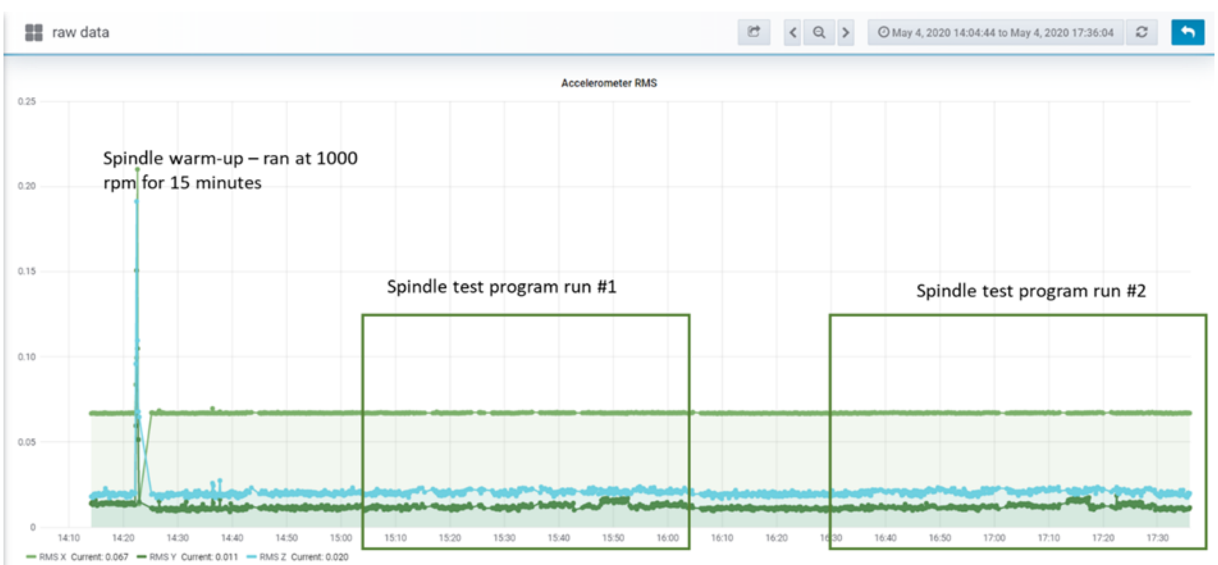

Figure 4: Accelerometer data for idle spindle tests; note that the node was mounted on the machine cabinet for the tests.

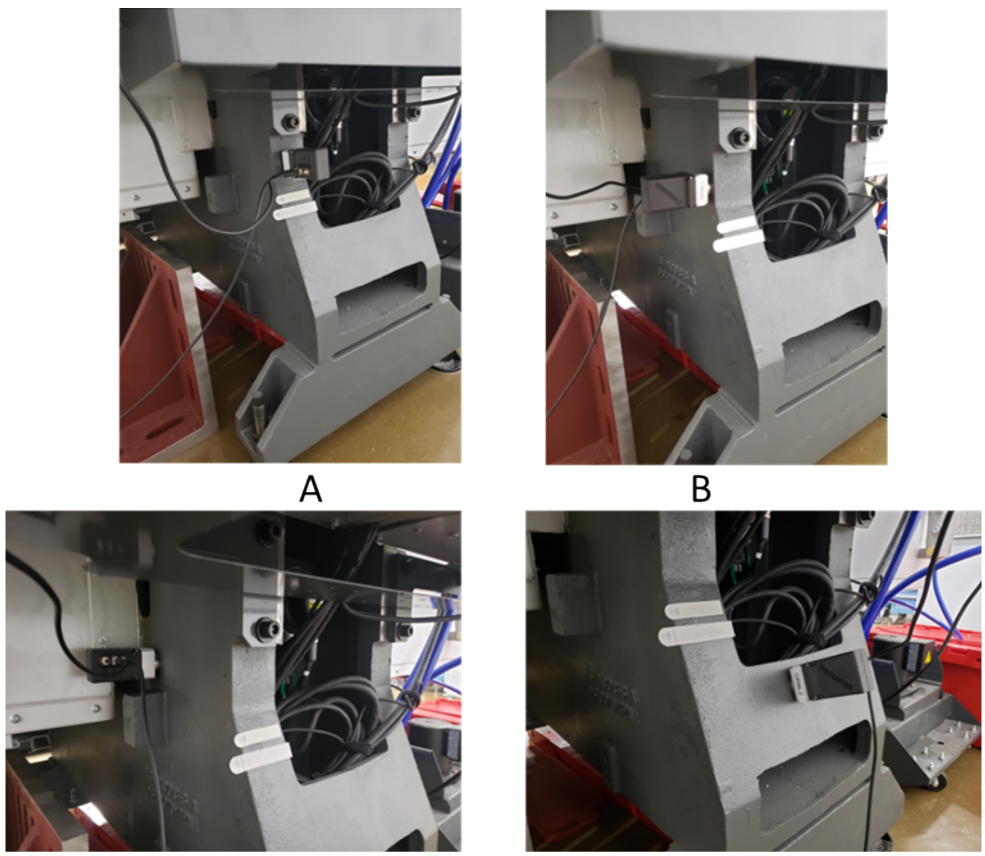

Figure 5: Locations for the Perisense node evaluated for accelerometer data.

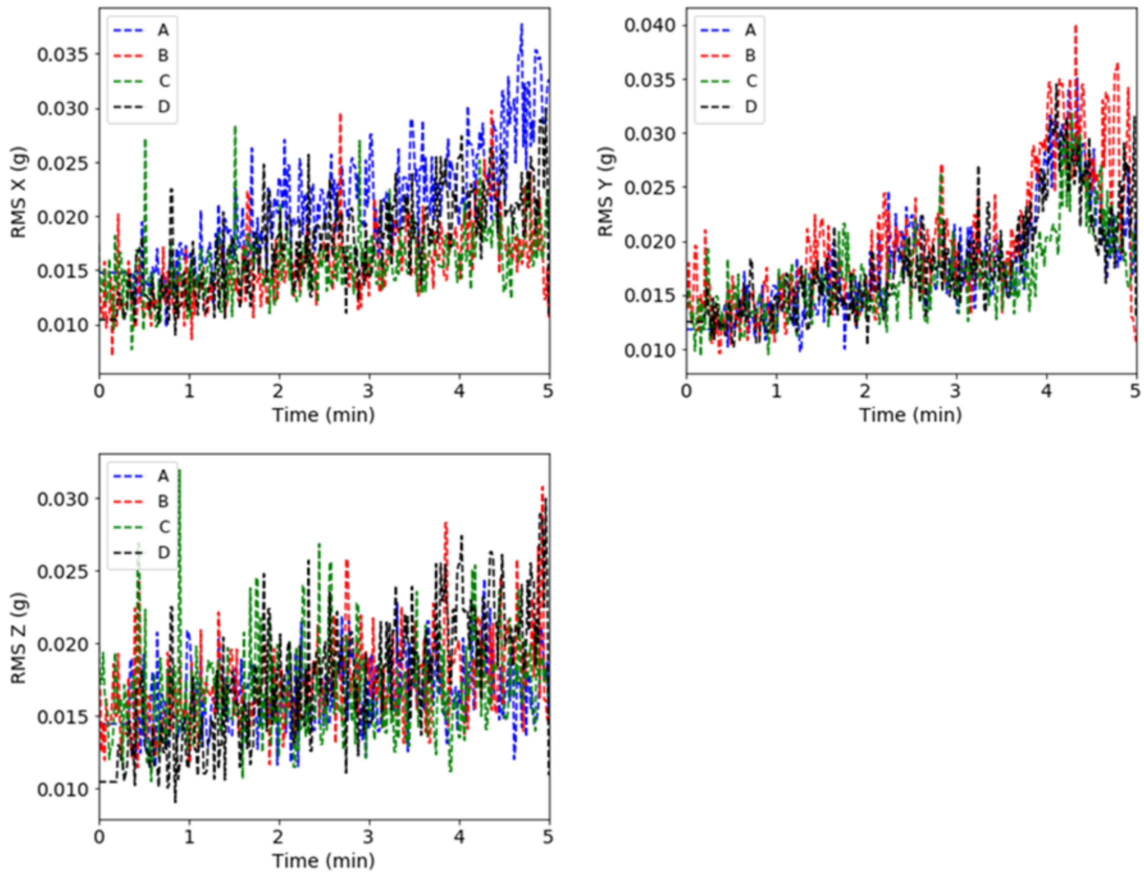

Figure 6: Accelerometer data in x, y, and z directions for the four locations tested.

4. CUTTING TESTS FOR PROCESS INSIGHTS

To evaluate the influence of cutting parameters on the sensor signals, cutting tests were performed. Tests were completed at different spindle speed, axial and radial depths of cut using a four-flute 38.1 mm diameter tool. Table 1 shows the test parameters.

Table 1: Test parameters for the cutting tests

Tests	Spindle speed (rpm)	Feed (mm/tooth)	Feed (mm/min)	Axial depth (mm)	Radial depth (mm)	Radial immersion (%)
1	1000	0.1	400	2	3	7.87
2	1000	0.1	400	2	6	15.75
3	1000	0.1	400	2	9	23.62
4	1000	0.1	400	2	12	31.50
5	1000	0.1	400	4	3	7.87
6	1000	0.1	400	4	6	15.75
7	1000	0.1	400	4	9	23.62
8	1000	0.1	400	4	12	31.50

9	4000	0.1	1600	4	3	7.87
10	4000	0.1	1600	4	6	15.75
11	4000	0.1	1600	4	9	23.62
12	4000	0.1	1600	4	12	31.50
9	4000	0.1	1600	8	3	7.87
10	4000	0.1	1600	8	6	15.75
11	4000	0.1	1600	8	9	23.62
12	4000	0.1	1600	8	12	31.50

For each cutting test, the spindle load from the machine controller was noted manually. In addition to data from the Perisense accelerometer and the current sensor, cutting force data from a Kistler dynamometer was also collected. Figure 7 shows the Perisense current data as a function of spindle load. The left figure shows the raw data and the right figure shows results after idle spindle speed correction (using data shown in Fig. 2). As seen from Fig. 7, the current sensor shows a linear relationship with the spindle load percentage recorded by the machine controller. Furthermore, results show that there is no dependence on spindle speed. Note that the values from both Perisense current sensors were identical. Therefore, data from one current sensor is shown in Fig. 7. Using Fig. 7, the spindle current can be used to calculate the spindle load utilization of the machine. Currently, the Perisense dashboard can detect if the spindle is running or not running based on a threshold value for the current sensor. Using the idle spindle speed current values, the current sensor may also be used to detect the ‘spindle idle’ or ‘air cut’ condition. This metric is useful to detect three machining situations:

1. the machining parameters are conservative taking small cuts leading the machine spindle to be under-utilized (as measured by spindle load);
2. inefficient programming methods leading to multiple air-cut tool paths in a part program;
3. manual recuts by the operator leading to a higher percentage for spindle idle conditions.

A new metric, called Machine Load Utilization is proposed which provides information on the percentage of time when the spindle is running, but the spindle load is less than 10%.

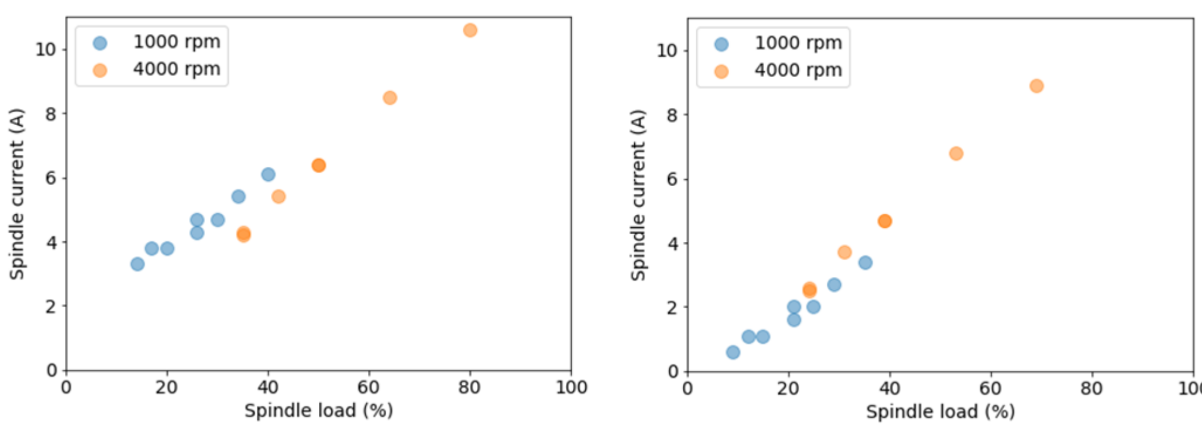

Figure 7: Spindle current as a function of spindle load percentage from the machine controller; the left panel shows the raw data and the right panel shows data with the idle spindle speed correction.

Figure 8 shows accelerometer data in *x*, *y*, and *z* directions as a function of spindle load; the idle correction has been applied using the data shown in Figure 6. The accelerometer node was mounted in location A (shown in the top left of Fig. 5). As seen from Fig. 8, the accelerometer data also increases linearly with spindle load. Like the current sensor, the accelerometer data can also be used to detect under-utilization of the machine spindle. For repeat operations on a machine, the accelerometer data can detect machine structural health. For example, a degradation of the spindle or the bearing will cause the accelerometer values to increase. For repeat operations, the maximum values can be noted from a calibration cycle and subsequently compared to continuing operations. If the accelerometer values increase over time, it can point to issues with the machine health. To reduce the noise in the accelerometer data, the total acceleration was calculated and plotted as a function of spindle load with the idle correction; see Fig. 9. The application of accelerometers for machine health monitoring will be further investigated in Phase 2. As noted, cutting force data was collected for the tests using a Kistler dynamometer. For each test, the average force in *x*, *y*, and *z* direction was calculated. Figure 10 shows the spindle current as a function of the mean force in *x*, *y*, and *z* direction. As seen from Fig. 10, there is a spindle speed dependence on the spindle current relationship with the cutting force.

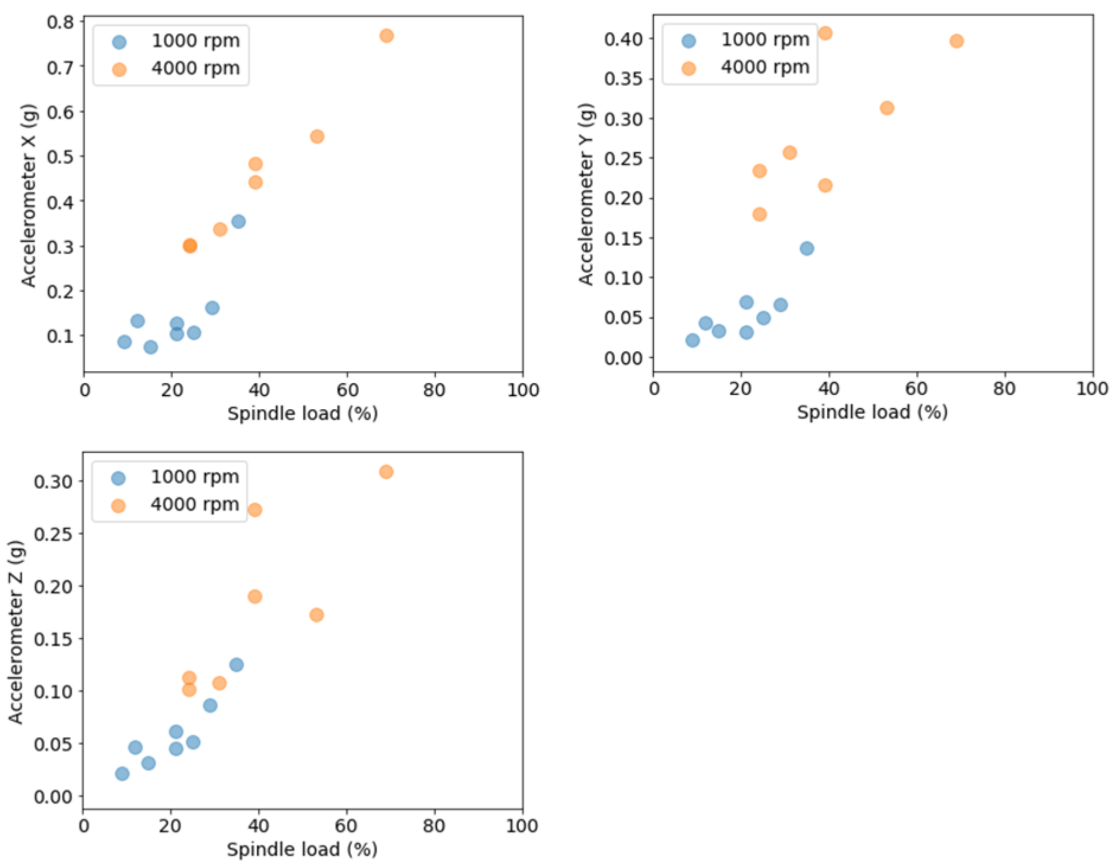

Figure 8: Accelerometer data in x, y, and z directions as a function of spindle load with the idle spindle speed correction.

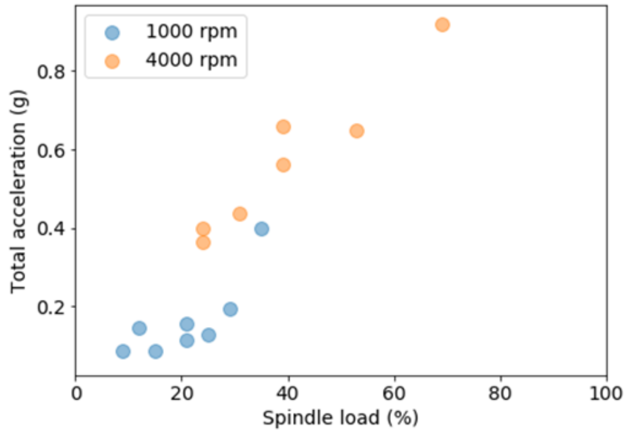

Figure 9: Total acceleration as a function of spindle load with idle spindle speed correction.

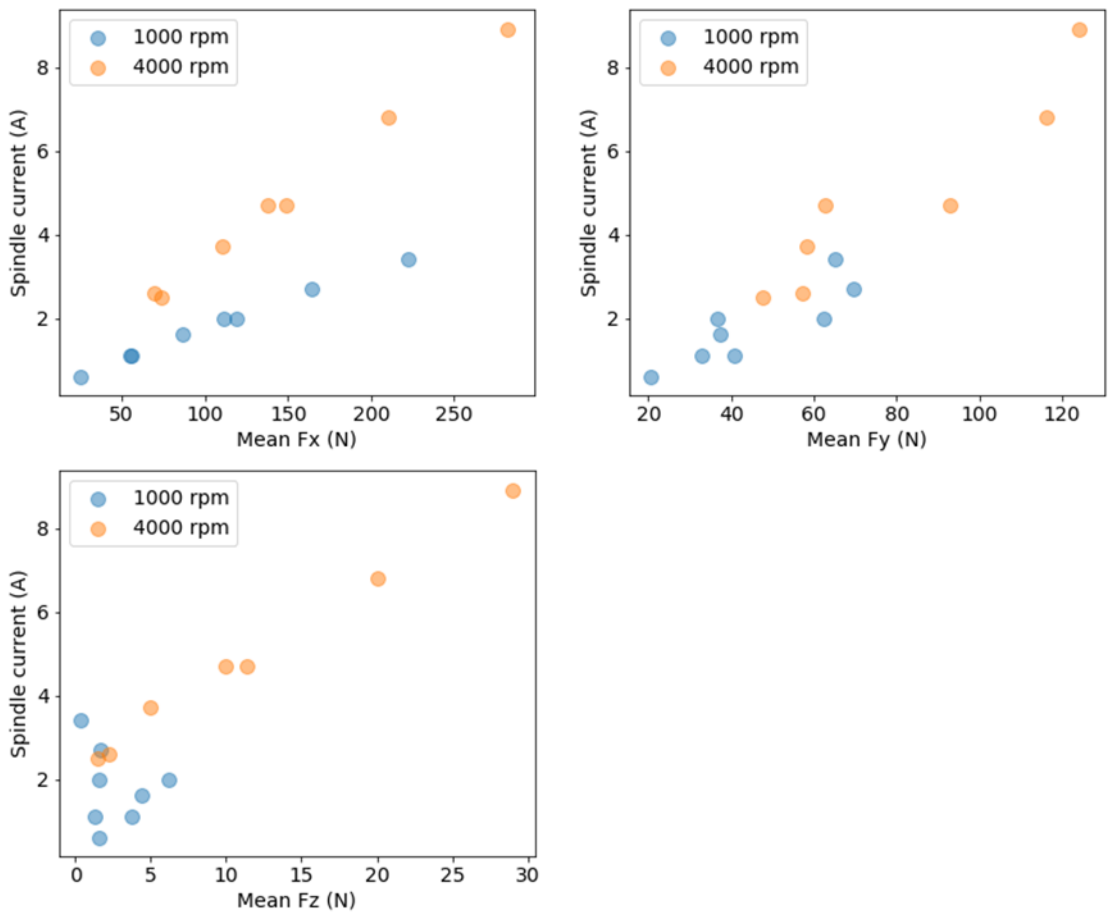

Figure 10: Spindle current, with idle spindle speed correction, as a function of the mean force in x, y, and z direction.

To evaluate the relationship with cutting force further, the total average cutting force and the cutting power was calculated for each test cut using Eq. 1 and Eq. 2.

$$F_{mean} = \sqrt{F_{x_{mean}}^2 + F_{y_{mean}}^2 + F_{z_{mean}}^2} \quad (1)$$

$$Power = \frac{K_s MRR}{6 \times 10^4} \quad (2)$$

In Eq. 1, F_{mean} is the average mean force for each test cut, and the subscript x, y, and z denote the direction. In Eq. 2, *Ks* is the specific cutting force coefficient for aluminum and was taken as 600 N/mm^2. Figure 11 shows the spindle current as a function of the total average cutting force and the cutting power for each cut. As seen from Fig. 11, the spindle current does not show a linear relationship with the average cutting force or the cutting power. For the Haas TM1 machine, the machine controller uses the spindle current to determine load percentage. As a result, the spindle current shows a linear relationship with the spindle load from the controller, but not the cutting power calculated using the measured cutting force.

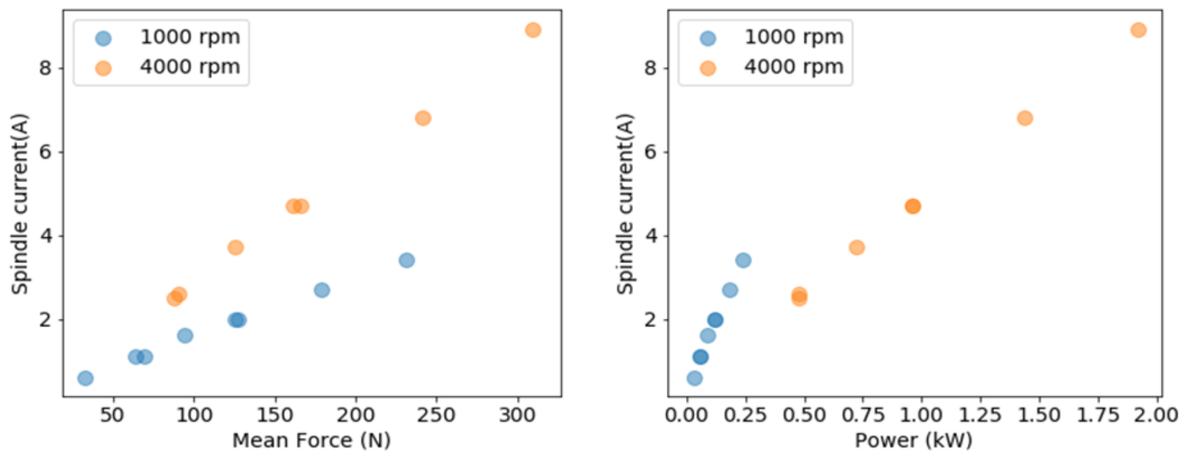

Figure 11: Spindle current, with idle spindle correction, as a function of the total average cutting force and the cutting power for each cut.

5. NEW SENSORS FOR MACHINING PROCESS MONITORING

To gain additional insight into the machining process, a power sensor was installed on the Haas TM1 machine. The power sensor measures the spindle power as follows. The power cell has three balanced hall effect sensors, each with a flux concentrator. Each phase passes through a window. A voltage sample for each phase is also taken. The hall effect semiconductor does a vector multiplication of the current flow and voltage which also calculates the power factor. The output is proportional to the spindle power. Figure 12 shows the power sensor installed on the Haas TM1 machine. A microphone or acoustic sensor will also be evaluated to monitor process steps like tool change, and machine door open/close. Phase 2 will include cutting tests to evaluate the power sensor and the microphone.

Figure 12:Power sensor installed on the Haas TM1 machine.

To perform frequency analysis, high frequency data was collected from the Haas TM1 machine using PCB accelerometers. The accelerometers were mounted in the same location as the Perisense node. The spindle speed sweep code program was run (as described in Section 2.0), and accelerometer data was measured at 10KHz sampling frequency. A Fast Fourier Transform (FFT) was completed at each spindle speed and the frequency for the maximum amplitude was noted. Figure 13 shows the results. The program was repeated two times. As seen from Fig. 13, different frequencies are excited at different spindle speeds. To illustrate, Figure 14 shows the FFT at 3100 rpm, 3200 rpm, and 3300 rpm for the two runs. As seen from Fig. 14, the frequency with the maximum amplitude shifts from 2257 Hz at 3100 rpm to 525 Hz at 3200 rpm and 3300 rpm. The 2257 Hz frequency is not excited at 3300 rpm. Phase 2 will focus on identifying the source for the underlying frequencies and evaluating the potential for machine health monitoring with the frequency analysis. Phase 2 will also focus on exploring the possibility for faster sampling of the accelerometer data from the Perisense node enabling frequency analysis.

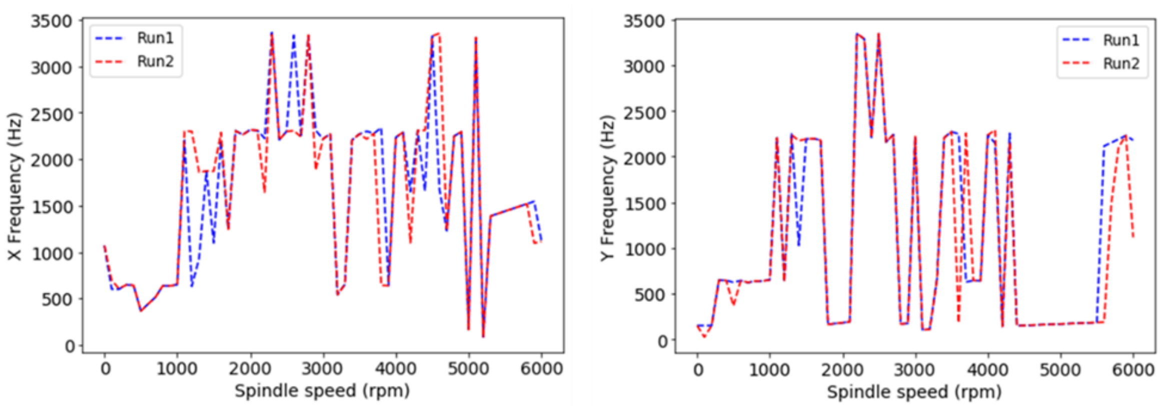

Figure 13: Frequency with the maximum amplitude from the FFT as a function of spindle speed.

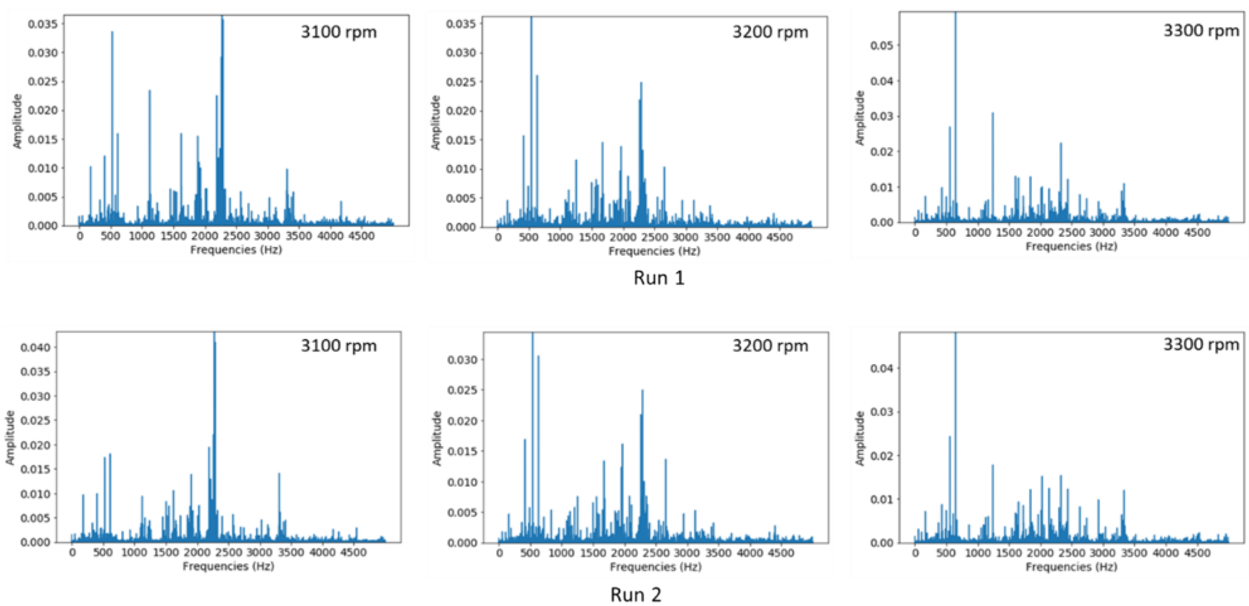

Figure 14: FFT at 3100 rpm (left), 3200 rpm (middle), and 3300 rpm (right) for run 1 (top) and run 2 (bottom).

6. PHASE I RESULT SUMMARY

The following insights can be summarized from Phase 1 testing.

1. The current sensor should be installed on the spindle drive to measure the spindle current. The values from both current sensors were identical. Therefore, one current sensor can be eliminated or installed on the main power for the machine to monitor the energy consumption of the machine.
2. The sampling frequency for the sensors needs to be reduced to one second to detect short-duration machining process insights. To achieve this, the nine-second sleep time should be eliminated.
3. The spindle current can be used to monitor the spindle load on the machine; this can be used to calculate the spindle load utilization of the machine.
4. The best location for the accelerometer for the Hass TM1 machine is on the *z*-axis column at the base of the machine. The accelerometer is also correlated to the spindle load of the machine.
5. Idle spindle speed tests can be performed periodically to detect machine health degradation. This is done by calibrating the machine at the start and comparing the accelerometer values to the calibrated values. For repeat parts in mass production, a similar analysis can be performed where a calibration cycle is performed for the first part.
6. Frequency analysis using high-frequency accelerometer data shows promise for detecting specific issues with machine health.