

Calibration and Implementation of a Torque and Temperature Sensor-Integrated Tooling System for End Milling

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Abstract

A transmitter system has been developed to collect high bandwidth data from torque and temperature sensor integrated cutting tools. The system is useful for collecting high resolution end milling torque and tool temperature during cutting without interfering with the cutting process. To achieve this, a Bluetooth transmitter and data conditioning system has been designed and integrated into an end milling tool holder. The wireless unit transmits a signal from a dual sensor-amplifier system. The system is designed to power and sample a variety of dynamic sensors including accelerometers, strain gages, and thermocouples. The tool holder can simultaneously sample two sensors from a sensor integrated end milling tool. These sensors reside inside of the endmill tooling and interface via an electrical connector within the tool holder. The compliance of the tool and tool holder are unaffected by the sensing system. A tool integrated with a torque sensor and thermocouple is demonstrated. The system is calibrated and cutting torque and tool temperature signals are observed.

1 INTRODUCTION

To advance current physical modeling and process monitoring capabilities in machining, it is necessary to develop and explore new methods of retrieving high resolution data from the tool-workpiece interface during cutting. Retrieving data directly from the cutting tool circumvents problems such as coupling, noise, and changing efficiencies. Recent advances in wireless sensor technology have explored the use of single-sensor integrated tooling for sampling tool tip conditions for vibration and temperature [1, 2, 3, 4]. Because of its high bandwidth and resolution, tool tip vibration data has been particularly useful for studying tool runout, chatter, and wear. The vibration amplitude is relative to the spindle speed and cutting geometry [1], and as a result, it does not directly provide cutting forces or torque information. Although tool tip vibration is valuable for monitoring dynamic effects, it is more useful to directly monitor causative variables such as tool forces.

With multiple sensor options available for studying end milling cutting dynamics, it is desirable to standardize a transmitter design to

sample a variety of sensors from a single receptacle located in the tool holder. In particular, the ability to simultaneously sample multiple sensors can improve resolution on the end milling system [6]. Therefore, a data wireless transmission method must be generalized to accept and simultaneously sample multiple sensors from within sensor integrated tooling. Given that multiple sensors improve the ability to resolve the milling system, three questions emerge:

1. Of various sensor options (e.g. vibration, acoustic, torque, thermal...), which sensors provide the most direct observation of tool conditions? In other words, "If your cutting tool could talk, what would it tell you?" At the International Machine Tool Trade Show (IMTS) 2008, UNH posed this question to machinists and manufacturing engineers from a multitude of metal cutting industries, job shops, and research labs. Despite the diversity of their backgrounds, their answers all expressed a desire for feedback about cutting power (torque) and tool temperature.

2. Which sensors are the most stable and reliable under harsh conditions of vibration, temperature, and fatigue? Among temperature sensors, thermocouples provide the best range, form factor, and immunity to vibration. To capture torque, wire or semiconductor gage bridges emerge as the most durable options for implementation on a cutting tool.
3. With a finite wireless bandwidth, what is the minimum number of sensors needed? With torque and temperature, high bandwidth dynamic phenomenon and energy transfer can be observed together. Torque is essentially high bandwidth energy measurement and temperature helps understand how much energy is transferred through the cutting tool.

From an academic perspective, torque and temperature also emerge at foremost significance to understanding tool condition. Direct measurement of both tool torque and temperature provides corroborating evidence of the tool and cutting conditions. Torque information captures high bandwidth effects from dynamic engagement of the cutting tool while temperature provides an observation of power dissipated through the tool. Instantaneous cutting power can be computed by integrating this torque signal. Combining torque and temperature data, analysis of cutting conditions can be made from energy models. Furthermore, unlike vibration sensors [5], torque bridges and thermocouples are not susceptible to drift in the sensor output at expected elevated temperatures.

Practical Considerations

Current commercial rotating sensor systems require slip rings or receivers in close contact proximity to the signal source [7]. This limits practical applications on the shop floor due to harsh environments, chip control, and fluid use. In an example by Dini et. al [8], close proximity wireless acquisition of cutting torque signals was conducted using a commercial rotating dynamometer. In this case, the dynamometer was directly placed between the spindle and tool. This method is excellent for capturing a torque signal, however, commercial dynamometers are high in cost and increase the spindle compliance. In a practical application, the spindle stiffness must be maintained in order to hold surface tolerances and prevent

conditions that may lead to tool chatter. In addition to increased compliance, the workspace envelope is reduced by placement of the commercial dynamometer between the spindle and tool holder. Since the cutting energy provided by torque is of primary interest to end milling process modeling and control, it is important to develop more robust sensor methods.

Due to the cost and limitations of current commercial sensor systems, machine tool manufacturers have been hesitant to accept sensor integration techniques. Although work such as [9] explores inexpensive machine tool sensor solutions, there are numerous factors beyond sensor cost and performance. For machine tool manufacturers, the scalability of sensor systems is a major concern. Since machine tools have a long operational lifespan, the sensor system must be reconfigurable and non-invasive to the machine tool platform. Simply, it must be fast and easy to upgrade when new sensing techniques become available or if the sensor system becomes damaged. For a wireless sensor integrated tooling system to be accepted by industry, the following criteria must be met:

- Does not increase the compliance of the cutting system
- Compatible with existing tool types
- Interchangeable sensor types
- Significant range and bandwidth while avoiding interference
- Inexpensive
- Easy to install, replace, and reconfigure
- Open for custom software development and controller integration

A system that meets these criteria can contribute to the evolution of NC machine tool control, cutting process monitoring, and accurate modelling of the cutting system. This work describes the calibration of a high bandwidth stereo transmitter and data acquisition system capable of supporting multi-sensor integrated tooling. The system is demonstrated to transmit both torque and temperature signals from a sensor integrated tool.

2 BACKGROUND

The amplifier and transmitter circuits are exterior of a C40 set screw type tool holder. A Lexan shield protects the electronics from im-

pact and fluid. The tool holder was modified to house a watertight six pin connector and route signal cables to the amplifier circuit. No modifications were made to alter the compliance of the tool holder body. Figure 1 shows the tool holder with the amplifier circuit in the shroud. For further clarity, video demonstrations of the device in operation are made available at [14].



Figure 1. Torque Temperature Smart Tool

Data is collected from both thermocouple and torque sensors in the tool. This data is sampled and transferred by a microprocessor on the tool holder body. The tool holder communicates to a PC via a Bluetooth Serial interface. The data route is shown in Figure 2 as a block diagram.



Figure 2. Block Diagram of Sensor System

Wireless Data Transmission Method

In an endmilling system, significant challenges to wireless bandwidth may exist from motor noise. During the machining process, spindle and bed motors generate a wide and continually changing spectrum of interference. This may increase the difficulty of wireless transmission with fixed frequency or amplitude methods. The problem can be approached in two ways: Characterizing the spectrum of motor noise and designing a transmitter to avoid it for a particular milling process, or, employing an active noise avoidance scheme such as frequency hopping spread spectrum (FHSS). Because of the multitude of mill configurations and processes, it is desirable to choose the second technique, since it is most amicable to generalization.

Since 1998, FHSS techniques have been commercially standardized for use on the license-free ISM band (2.4-2.4835 GHz). This standardization has been motivated by attention from the communications hardware industry, with one particular standard being defined through the Bluetooth Special Interest Group [10]. High quality audio transmission has been at the forefront of this technology with interoperability between all Bluetooth audio devices being based on the Audio Distribution Model [11]. Transmission bandwidth requirements conform to mandatory sampling requirements of 44.1 and 48.0 kHz. These rates are enforced for the benefit of the transmitter by the receiver device [11].

For this work, a smart tool holder prototype was constructed with custom electronic hardware and a digital serial transmitter. A 16 bit A/D is used to sample torque at 10 kHz and a 12 bit thermocouple junction/sampler is used to capture temperature three times per second. To minimize phase effects in the data, no data compression protocols were deployed in the system. The Bluetooth serial transmitter conforms to the published specifications in [10]. The analog signal conditioning circuit on this particular transmitter has a high frequency rolloff with a corner frequency at below 4 kHz to prevent aliasing in the digital signal. The effective frequency bandwidth of this transmitter is approximately 0 Hz to 3.4 kHz.

3 EXPERIMENTAL DESIGN

Evaluating the Temperature Sensor

The temperature sensor is embedded axially in the core of the 19.05 mm insert holder body. Therefore, it is necessary to determine how the sensor responds with respect to an applied temperature condition on the cutting edge of the tool. To do so, a temperature boundary condition is applied with a feedback controlled heating element. The temperature condition is applied to simulate a 0.254 cm (0.1 inch) axial engagement. All of the tools tested are commercial carbide cutting tools. A second research goal of this experiment is to determine if the insert coating type has a significant effect on the time constant, phase, and gain of the temperature signal. Two different uncoated tools, TiCN, and TiAlN coatings were compared. It is hypothesized that the coating plays a minimal effect on the heat transfer observed by the embedded thermocouple. However, this hypothesis must be confirmed to ensure proper sensor calibration. The thermal conductivity of tungsten carbide is approximately 84 W/m/K whereas the conductivity of thin coatings such as TiN is less than 20 W/m/K [15]. Figure 3 shows a picture of the temperature control setup in the milling machine and a thermal resistance network.

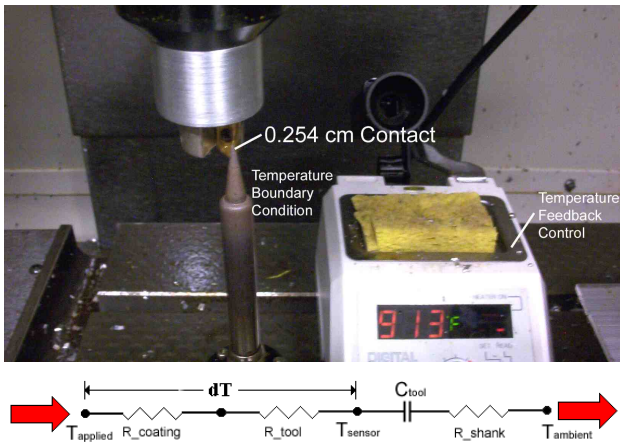


Figure 3. Experimental Temperature Setup

To test the performance of the temperature sensor and determine if insert coating has an effect on the sensor response, a Balanced Incomplete Block design was implemented. For each condition, the time constant and gain of the temperature signal was observed from the data. The coating materials inspected change their heat transfer coefficients as a function of

temperature. For example, the thermal conductivity of TiN is 28.84 W/m/K at 25°C and changes to 16.72 W/m/K at 200°C [15]. Therefore, the block unit for this experiment is Temperature. The variation in the heat transfer due to the applied temperature is not of interest. The comparison made between the coating types is separated from the effect of temperature. Table 1 details the experimental design.

Block Temperature °C	Treatments (Insert Coating)		
150	Uncoated 1	TiN	TiAlN
250	Uncoated 1	TiN	Uncoated 2
350	Uncoated 1	TiAlN	Uncoated 2
485	TiN	TiAlN	Uncoated 2

Table 1. Block Design of Temperature Tests

The observed temperature response shows an exponential approach to steady state. This agrees with the experimental setup of a RC thermal resistance circuit. This data is fit to estimate a time constant. The time constant is useful for understanding the frequency resolution on the temperature. In addition to estimating the time constant, the gain between $T_{applied}$ and T_{sensor} can be given as a ratio:

$$Gain = \frac{T_{sensor}}{T_{applied}} \quad (1)$$

where T_{sensor} is the steady state thermocouple temperature and $T_{applied}$ is the heating temperature.

Figure 4 shows an example temperature response, estimated time constant, and gain.

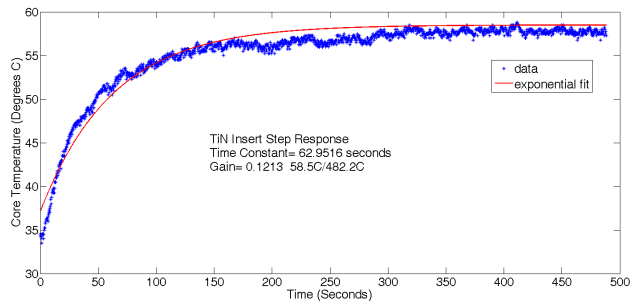


Figure 4. Temperature step response

To observe if the coating value has an effect on the time constant or gain, the time constants and gain values were collected for all of the cases in Table 1. These values were analyzed in the JMP statistical software package to determine if an effect existed as a function of temperature. A standard least squares model

was used to estimate time constant as a function of coating. The temperature variable was modeled as a random effect nested with coating type. Figure 5 shows the least squares means for coating types with standard error.

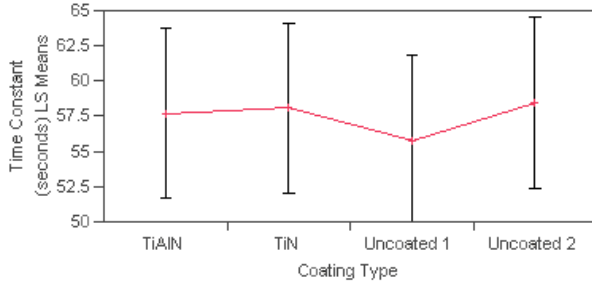


Figure 5. Time Constant LS Means

The overlapping standard errors shows that time constants have insignificant differences. Because the coatings are thin films and thermal resistance is a function of thickness, it is not surprising that the coating has a negligible effect on the time constant.

Unlike time constant, the gain value is influenced by the tool type. Figure 6 shows a least squares mean plot of gain values with corresponding standard error.

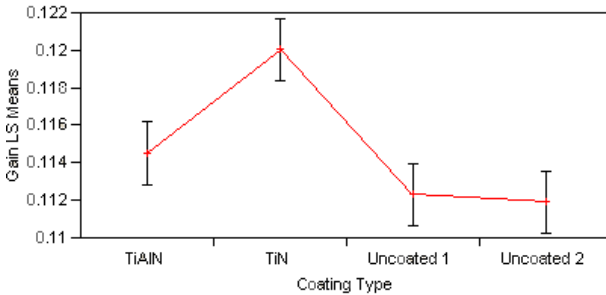


Figure 5. Gain LS Means

The TiN coated tool appears to have a slightly higher gain value compared to the other tools tested. Since the standard errors do not overlap, this difference is significant. This is insightful, since the gain value relates the thermal resistance of the coating plus the tool substrate. If the gain increases, the thermal resistance ($R_{coating} + R_{tool}$) between $T_{applied}$ and T_{sensor} decreases. However, there is no observed effect in the time constant for the TiN coated tool. Thus, for the time constant, $\tau = (R_{coating} + R_{tool}) \times C$, to remain the same, the value of C must increase.

This effect can be attributed to unknown substrate properties between the tool types tested. The experiment assumes that the carbide substrate is identical between tool types.

It is likely that the substrate carbide for the different tools contains slightly different percentages of a binder material such as cobalt.

From this experiment, the accuracy of the temperature sensor can be quantified by the gain. The gain value is $0.115 \pm 0.0036^\circ\text{C}$. The resolution of the temperature sensor is $\pm 3.64^\circ\text{C}$ at full scale of 1023.75°C . The time resolution can also be quantified from the time constant 57.496 ± 4.040 seconds. Changes of temperature less than 0.0028 Hz (changes in average temperature) can be resolved. For this sensor integrated tool, the expression for estimating mean temperature at the tool-workpiece interface is:

$$\bar{T}_{interface} \approx \frac{T_{core}}{0.115} \quad (2)$$

This expression is the fixed temperature sensor calibration. The temperature calibration experiment confirms that different tool coatings do not require recalibration of an embedded thermocouple sensor. This is useful in practice where different inserts may be deployed without modifying the sensor system. Furthermore, the time resolution of the sensor demonstrates that the tool-core location of the thermocouple is appropriate for estimating the mean temperature of the tool-workpiece interface.

Calibrating the Torque Sensor

Calibrating the torque sensor is less cumbersome than characterizing the response of the temperature sensor. In the desired bandwidth, the behavior of the torque gage is linear and can be understood by applying a static moment of different known values. The torque sensor is a full bridge shear arrangement to negate temperature and shaft bending effects. The torque resolution is 16 bits sampled at 10 kHz. Figure 6 shows the calibration points of the torque sensor and linear data regression.

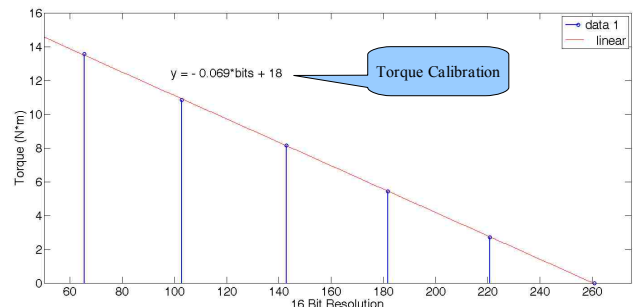


Figure 6. Torque sensor calibration curve

Phase Between Temperature and Torque

Simultaneous sampling of both torque and temperature exposes the phase delay of the temperature sensor. This is expected since heat must transfer through the thermal mass of the tool body. To quantify this value, a cutting test is conducted and the high bandwidth torque signal is used as a reference. Figure 7 is a plot of a cutting test, showing temperature time-aligned with the torque signal.

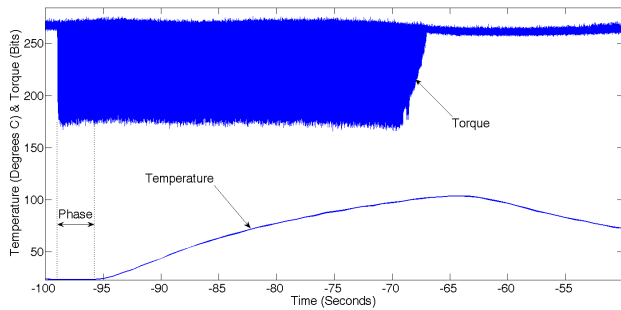


Figure 7. Temperature phase delay

The temperature is observed to lag the torque signal by approximately 4 seconds.

4 IMPLEMENTATION AND TESTING

After characterizing the sensor integrated tool, it is deployed in an end milling platform to explore practical applications. Both torque and temperature sensors are sampled simultaneously under a variety of cutting conditions. The inserts used for these tests are Sandvik R390-11 T3 08M-PM.

Steady State Temperature Test

Based on the calibration experiments for the embedded thermocouple, the temperature sensor is limited to near steady state changes in cutting temperature. A cut is conducted at 2500 RPM in tool steel with 3.175 mm axial depth, 9.525 mm radial engagement (half immersion of a 19.05 mm tool), and a feed per tooth of 0.122 mm/tooth. This test is designed to last 120 seconds~ 2 time constants.

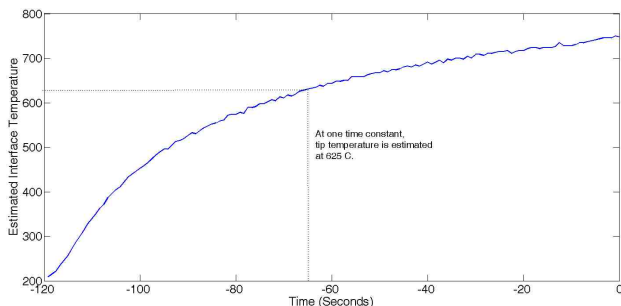


Figure 8. Cutting temperature test

Figure 8 shows the tool core temperature calibrated according to Equation 2. At one time constant, the sensor temperature is 63.2% of the steady state value. Therefore the cutting interface is estimated at 989°C during this experiment. The result is encouraging since it agrees with feasible tool-workpiece interface temperatures [16].

Estimating Tool Run Out from Torque Data

On a two insert cutting tool, the chip load is ideally distributed at 50% material removal rate (MRR) on each insert. Realistically, run out exists on the tools and it must be quantified. This eccentricity is expected on insert type tools and with set screw tool holding systems. The effect of run out is greatest after tool changes before the tools are 'broken in'. By knowing the torque, it is possible to understand the true distribution of MRR on the insert cutting tools. Figure 8 is a torque plot showing a case of insert run out.

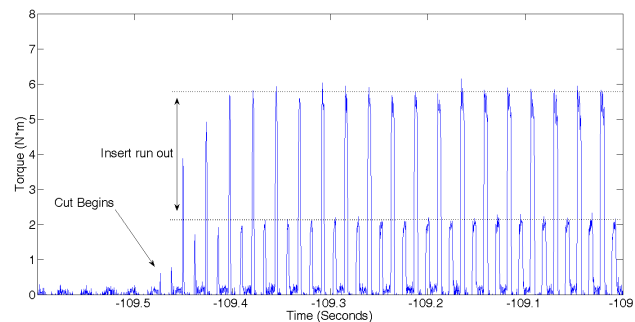


Figure 9. Torque signal during insert run out

By comparing the peak torque values, the distribution of MRR can be approximated. During the case shown in Figure 9, insert 1 is contributing 27% of the MRR capacity while insert 2 is contributing 73% of the MRR. The average feed per tooth of this test was 0.122 mm/tooth. As a result of insert run out, insert 1 cuts at an effective 0.0329 mm/tooth and insert 2 cuts at an effective 0.0891 mm/tooth.

This information about insert run out is useful to estimate surface finish, as input to dynamic models, and to forecast relative tool life.

Quantifying Tool Dynamics

Possibly the most interesting application of a this sensor integrated tooling system is the observation of tool tip dynamic effects. Previous work by [1] and [4] investigates a tool tip vibration sensor for observing the frequency content during regenerative tool chatter. Although

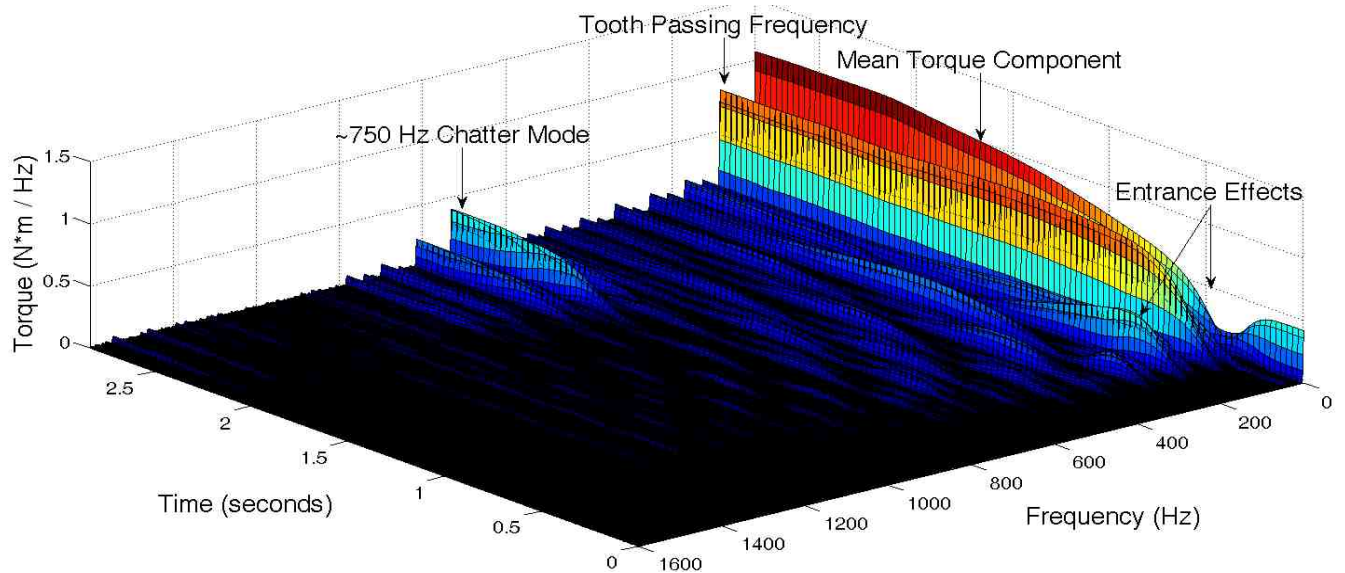


Figure 10: Torque signal showing entrance effects and regenerative tool chatter

vibration is a useful source of information to inspect frequency components of the cutting signal, it does not reproduce necessary force magnitude information. Unlike commercial rotating dynamometers, the sensor is integrated with a commercial cutting tool and the stiffness is not affected. Thus, modes are not artificially introduced into the cutting system. With the torque dynamometer integrated tool, a direct observation of the tool engagement is possible.

Since previous work investigated tool chatter with tool tip vibration, a test is conducted to observe chatter with the torque sensor integrated tool. A cut is conducted in tool steel with a 14.2875 mm radial engagement and 3.175 mm axial depth. At a spindle speed of 2500 RPM, a light chatter condition was encountered. Figure 10 shows a waterfall plot of this test. The evolution of the chatter mode reflects the results of [4]. However, unlike previous vibration studies, the force magnitude information is preserved. Over a time period of approximately 0.5 seconds, the amplitude of the chatter mode grows to between 0.5 N*m and 1 N*m.

In addition to tool chatter, the dynamics of workpiece entrance and exit are shown. Specifically, when the milling tool initially contacts the workpiece, the behavior is notably different than during steady state cutting. Although this effect influences surface quality, the author is not aware of literature thoroughly documenting the dynamics of the tool during this period of rapidly changing engagement. Figure 10 highlights the workpiece entrance effects at the beginning of the test. The frequency content of the torque data suggests that the response of

the milling system experiences substantial changes during the entrance.

5 CONCLUSIONS

The calibration of temperature sensor is not significantly affected by the type of insert coating deployed in the tool holder. This is essential for deploying the temperature sensor in a production environment. However, the time constant and phase of the temperature sensor are larger than desirable. Therefore, the temperature calibration experiment has resulted in an opportunity to improve the temperature sensor system to reduce the lag and time constant. The torque sensing system on this tool was determined to be linear and is successfully calibrated to provide torque in N*m. Since the torque data captured by this system retains correct force magnitudes, it is more useful than vibration data. The high bandwidth torque signal was demonstrated to quantify tool run out and capture dynamic phenomena.

6 CURRENT AND FUTURE WORK

Current development work focuses on placing the temperature sensor inside the tool holder body at a closer physical distance to the insert tool. Although it is straightforward to place a thermocouple near the insert cutter, the challenge is designing the sensor system so that it is practical to assemble. The thermocouple must be embedded in the tool holder body in a way that is rapid to produce, protected from cutting, and unaffected by insert changes.

A collaborative goal is to seek interaction with FEA developers to deploy the smart tool

sensor system in corroboration with modeling techniques for deformation, dynamics, and heat transfer.

There are exiting opportunities to use a torque and temperature integrated tooling system for monitoring in-process dynamics and tool condition. Avenues for further research exist studying workpiece entrance and exit dynamics, relating torque and temperature through energy models, quantifying optimal cutting parameters (temperatures/feeds/speeds), wear modeling and failure prognoses, among other applications.

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