Int. J. Mechatronics and Manufacturing Systems, Vol.

A low cost wireless high bandwidth transmitter for sensor-integrated metal cutting tools and process monitoring

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Abstract: A transmitter system has been developed to collect high bandwidth data from sensor integrated cutting tools. The system collects high resolution end milling data during cutting without interfering with the machining process. A Bluetooth transmitter and instrumentation amplifiers are integrated into an end milling tool holder. The system is designed to power and sample a variety of sensors residing inside the tooling. The compliance of the tooling is unaffected by the sensing system. A tool integrated with a torque sensor is demonstrated. The cutting torque signal is compared to theory and experimental tests with a traditional bed type dynamometer.

Keywords: end milling; metal cutting; condition monitoring; bluetooth wireless; sensor integrated tool; torque dynamometer; accelerometer; vibration.

Reference to this paper should be made as follows: Suprock, C.A. and Nichols, J.S. (2009) 'A low cost wireless high bandwidth transmitter for sensor-integrated metal cutting tools and process monitoring', *Int. J. Mechatronics and Manufacturing Systems*, Vol.

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1 Introduction

To advance current physical modelling and process monitoring capabilities in machining, it is necessary to design new methods of retrieving high resolution data from the tool-workpiece interface during cutting. Recent advances in wireless sensor technology have explored the use of single-sensor integrated tooling for sampling tool tip conditions for vibration and temperature (Suprock et al., 2008a, 2008b; Sudararajan et al., 2005; Wright et al., 2006). 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 (Suprock et al., 2008a) and as a result, it does not directly provide cutting forces or torque information. However, if vibration is simultaneously sampled with or replaced by the cutting torque, the actual magnitude of the tangential cutting force can be determined. Since, vibration sensors using sealed electret condensers are susceptible to drift in the sensor output at elevated temperatures (Jones et al., 2008), it is desirable to replace or supplement vibration sensors with a Wheatstone bridge to provide direct cutting torque and immunity to temperature effects.

With multiple sensor options available for studying end milling cutting dynamics, it is desirable to standardise 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 (Roth, 2006). Therefore, a data wireless transmission method must be generalised to accept and simultaneously sample multiple sensors from within sensor integrated tooling. To this point, there have been no solutions that satisfy this need.

Commercial rotating sensor systems require slip rings or receivers in close contact proximity to the signal source (EE Times Asia, 2002). This limits practical applications on the shop floor due to harsh environments, chip control and fluid use. In an example by Dini and Tognazzi (2006), 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 modelling 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 Suprock et al. (2008c) 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 design and implementation of a high bandwidth stereo transmitter and data acquisition system capable of supporting multi-sensor integrated tooling. The system is demonstrated to transmit a torque signal from a sensor integrated tool. The transmitter and sensor system is designed to monitor machining dynamics and does not transmit the DC component of the signal.

2 Background

The amplifier and transmitter circuits are built into an ABS plastic shroud mounted on the exterior of a C40 set screw type tool holder. The tool holder was modified to house the female mini DIN 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 ABS plastic shroud and a block diagram of the data route. For further clarity, video demonstrations of the device in operation are made available at the UNH Design and Manufacturing Laboratory website (UNH DML, 2008).

Figure 1 Block diagram of wireless sensor system (see online version for colours)

2.1 Wireless data transmission method

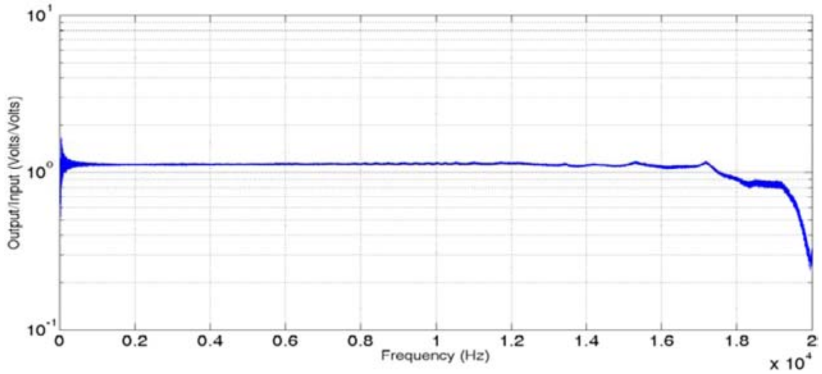
In an end milling system, significant challenges to wireless bandwidth may exist from motor noise. During the machining process, spindle and bed motors generate a wide and continually changing spectrum of interference. This may increase the difficulty of wireless transmission with fixed frequency or amplitude methods. The problem can be approached in two ways: Characterising 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 generalisation.

Since 1998, FHSS techniques have been commercially standardised for use on the license-free ISM band (2.4–2.4835 GHz). This standardisation has been motivated by attention from the communications hardware industry, with one particular standard being defined through the Bluetooth Special Interest Group (Bluetooth SIG, 2008). 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 (Bluetooth SIG, 2007). 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 (Bluetooth SIG, 2007).

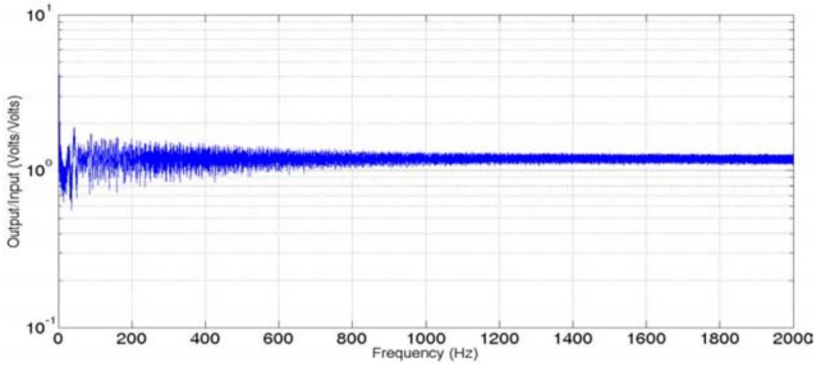
For this work, a commercially available 16 bit audio transmitter is used. The transmitter circuit is modified from a Com One A2DP stereo audio transmitter (retail cost approximately $40). This transmitter contains the necessary transceiver hardware and A/D circuit to transmit stereo voltage signals of ±1 volt. The A2DP transmitter conforms to the published specifications in (Bluetooth SIG, 2007) and is capable of sending a stereo audio signal to the Bluetooth receiver at 48.0 kHz. The analogue signal conditioning circuit on this particular transmitter has a high frequency rolloff with a corner frequency of 20 kHz. This is observed in preliminary testing of the device and exists to prevent aliasing in the A/D. The effective frequency bandwidth of this transmitter is approximately 10–20 kHz. Figure 2 details the frequency response of the transmitting unit. The frequency response is shown as a transfer function between the input and transmitter responses. The input to generate this transfer function is a sine chirp from 0 kHz to 20 kHz conducted over a one minute interval. This bandwidth is sufficient for observing high speed milling phenomena. For high clarity in common machining frequencies, the 0–2000 Hz band of the response has been characterised separately with a one minute 0–2 kHz chirp and is shown as a subplot in Figure 2.

Figure 2 (a) Full A2DP transmitter response and (b) low frequency transmitter response (transmitter voltage input/receiver voltage output) 0–20 kHz (see online version for colours)



(a)

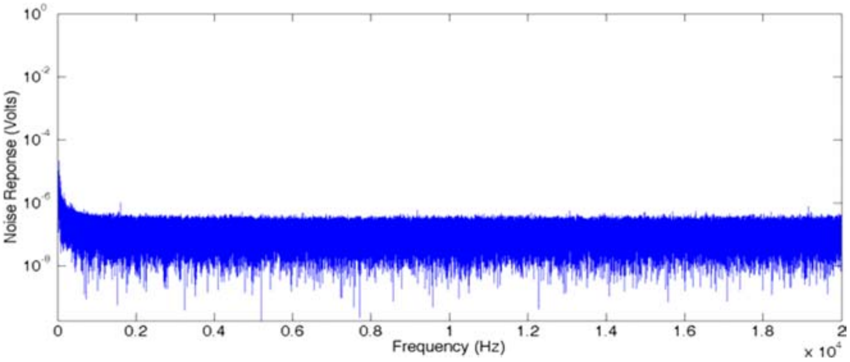
Figure 2 (a) Full A2DP transmitter response and (b) low frequency transmitter response (transmitter voltage input/receiver voltage output) 0–20 kHz (see online version for colours) (continued)



(b)

The noise floor of the transmitter is also evaluated to understand the lower limits of transmission resolution and the input amplitudes required for sending high quality data signals through the system. This experiment was conducted while the milling machine was on however the spindle was not rotating. Figure 3 shows the noise response spectrum of the transmitter. The noise introduced by the transmitter is found to be negligible and is on the order of 10^{-7} volts.

Figure 3 A2DP transmitter noise response (see online version for colours)



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The data integrity of this system is high and does not show degradation during the cutting tests conducted for this work. Using a FHSS transmitter with a packet resend command, no issues with multipath interference or Doppler effects were experienced. Under the Bluetooth standard, frequency hopping can occur at 1600 Hz, compared to feasible spindle rotation frequencies under 100 Hz. The receiver was placed on the door of the end mill in order to reduce the transmission path to a range less than 2 meters. With a frequency hopping transmitter, receiver position matters less than with a fixed frequency transmitter. However, range remains an important variable. The open path range of the transmitter used in this work is 10 meters. Work by Wang et al. (2008) provides a more comprehensive discussion of transmission integrity on rotating equipment.

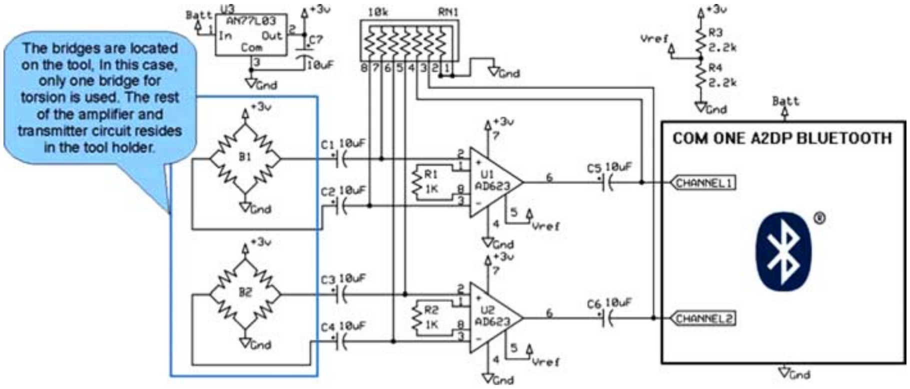
2.2 Pre-transmitter signal conditioning

The signal conditioning system is designed to support sensor integrated tooling on a 3 volt rail. The tooling interface is made through a six contact male mini DIN connector on the top of the tooling unit. A counterpart mini DIN connector is located inside of the tool holder. Analog Devices 623 instrumentation amplifier chips were selected as gain multipliers. The gain was set to 100 to increase the signal from low level sensor output to the ±1 range required by the Bluetooth transmitter.

Since this sensor system is designed to observe a dynamic process, capacitors were included in series with the sensor signal leads. These capacitors are a highpass filter that eliminates the low frequency components under a corner of 10 Hz. The capacitors eliminate any temperature effects in the lead wires (Beckwith et al., 1995) as well as reducing the power consumption of the sensors.

To power both the signal conditioning system and the Bluetooth transmitter, current is supplied from a 3.7 volt lithium ion battery. The voltage to the signal conditioning circuit is regulated by an AN77L03 3 volt regulator. This component is critical to prevent gain drift in the amplifier circuit as the battery discharges. The battery power supply and charging circuit are located on the Com One Bluetooth transmitter. Figure 4 details the signal conditioning circuit (located in the tool holder) and strain gage bridges located (on the sensor integrated tool). The sensor integrated tooling designed to work with this amplifier-transmitter tool holder is not limited to strain bridge circuits. However, to test this prototype, a torque bridge was constructed.

Figure 4 Dual strain bridge and amplifier circuit with amplifiers and regulator supply (see online version for colours)



The bridges are located on the tool, In this case, only one bridge for torsion is used. The rest of the amplifier and transmitter circuit resides in the tool holder.

The frequency response of the AD623 instrumentation amplifier is affected by varying the gain resistor load. With a gain resistor of 1 kΩ, the specified frequency response of this amplifier is 0 to approximately 10 kHz. To avoid aliasing in the digital signal, the A/D samples at 20 kHz. Although the specified amplifier response is to 10 kHz, the observed response attenuates at approximately 17 kHz. With a frequency response of 0–10 kHz, this amplifier circuit is sufficient for conditioning signals of all end milling phenomenon. With an analogue bandwidth up to 10 kHz and a sampling rate of 20 kHz, observation of the milling tooth passing frequency is possible up to a theoretical 300,000 RPM with a two flute tool.

2.3 Tool mounted torsional strain bridge

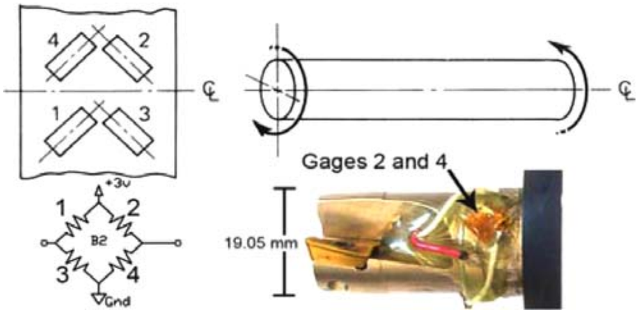
The bridge circuit is located on the outer radius of the end mill cutting tool. An indexable insert cutter, ISCAR HELI2000, was chosen for this work. This cutter represents a 'worst case' scenario for the measurement of strain. It is a short overhang tool with a 19.05 mm shank. However, it was estimated that wire gages would provide sufficient sensitivity for a torsion bridge. The relationship for sensitivity can be given as:

$$\frac{V_o}{V} = \frac{FTD_o}{2I_o E} \tag{1}$$

where V_o is the bridge output voltage, V is the excitation voltage, F is the gage factor, E is the material modulus, D_o is the tool diameter and I_o is the area moment of inertia. At a 3 volt excitation voltage, the sensitivity is expected to be approximately 4.3×10^{-5} V/(N*m). This is acceptable, considering the amplifier and software gains. With a 100x amplifier gain and a 10*x* software gain, the recorded voltage will reach ±1 volt when 23.2 N*m is applied to the tool.

Figure 5 shows the orientation of the torsion bridge gages along with a photograph of the location of gages 2 and 4 on the cutting tool.

Figure 5 Torque bridge on cutting tool with electrical diagram of gage bridge and schematic of gage layout (see online version for colours)

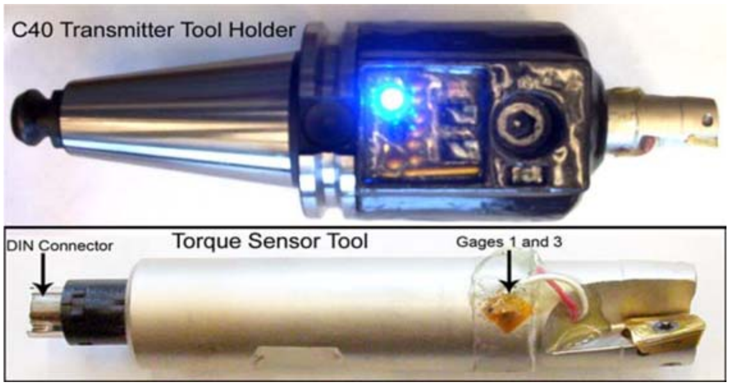


Although the amplifier and transmitter circuit are designed to send stereo signals, this tool outputs a single channel torque signal. This was done to test the gage sensitivity and to evaluate the effectiveness of the amplifier/transmitter circuits.

The tool used is a through-coolant design. The coolant channel provided a convenient route for the sensor signal wires without interrupting the cutting process or altering the physical geometry of the tool holder. Figure 6 details the position of the mini DIN connector and strain gage rosettes. Because of the prototype nature of this tool, the gages and signal wires were protected by epoxy and not fully encased by a protective cover.

Following a similar design scheme to the vibration sensor-integrated tooling systems described in Suprock et al. (2008a), this high bandwidth stereo transmitter includes a printed circuit amplifier board, symmetric geometry for low eccentricity and reduced wire routing for an improved signal to noise ratio. This prototype is also waterproof for experimental testing with cutting fluid. Figure 6 shows a profile of the transmitter tool holder design featuring the amplifier circuit facet.

Figure 6 Torque sensor integrated tool and transmitter (see online version for colours)



3 Testing

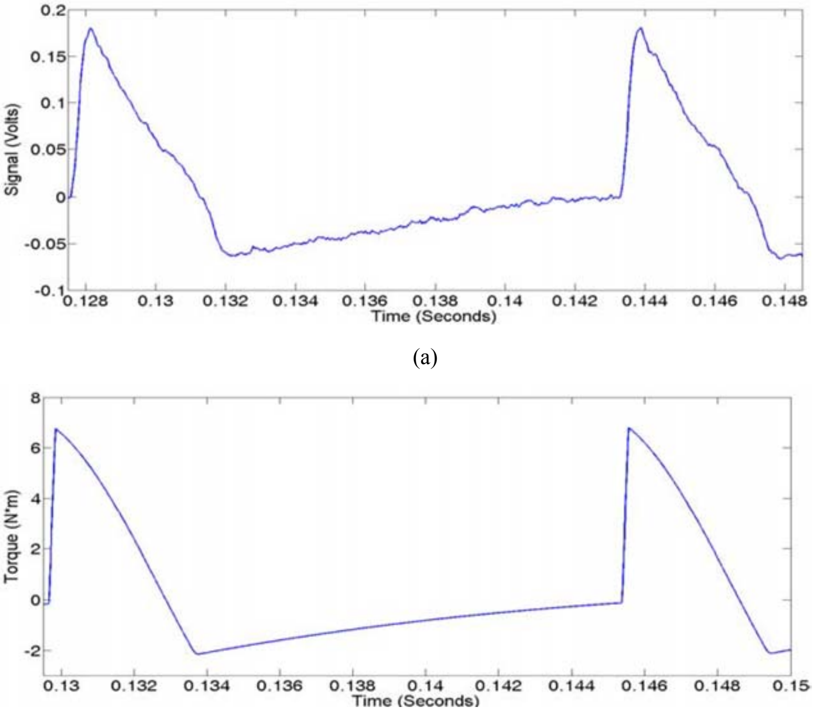
The primary use of the stereo transmitter prototype is to evaluate the functionality and feasibility of the proposed system. Since the tool tested was a torsion bridge setup, bending crosstalk was evaluated by impact tests on the radial direction as well as on the tangent of the tool. As expected, the tangential impacts generated a torque signal whereas radial impacts did not produce a signal above of the signal noise floor at 10^{-6} volts.

3.1 Model based verification

To estimate the integrity of the torque signal acquired by the sensor integrated tooling, the signal shape can be compared to the output of an analytical cutting force model (Xu et al., 2007). Although contrasting the experimental torque to the output from an 'ideal' model does not provide magnitude information, the signal shape of the experimental signal concurs well with the model signal characteristics. Figure 7 shows both the model and experimental torque plots.

The cutting parameters for this test are down milling, 1/8 inch axial engagement, 0.375" radial engagement, tooth passing speed of 3819 RPM, with an average chip thickness of 0.004" in 6061 Aluminum. The cutting force model used to help generate the simulated results of Figure 7(b) is a validated mechanistic model detailed in Xu et al. (2007).

Figure 7 (a) Experimental torque data recorded during cutting and (b) simulated torque data from cutting force model (see online version for colours)



(a)

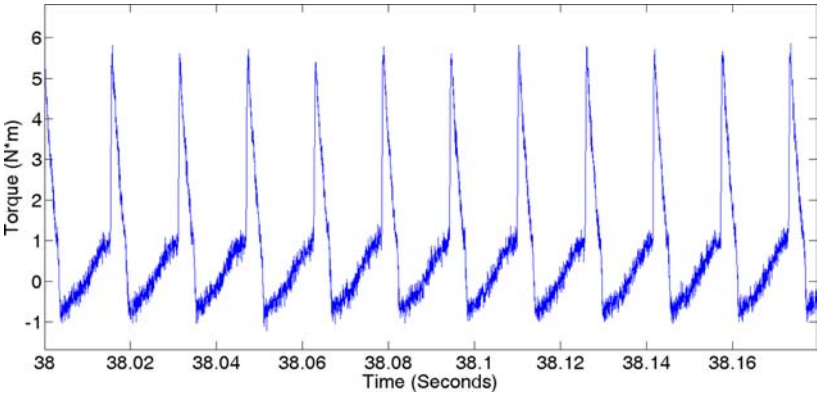
(b)

It may be be noted that the experimental plot shown in Figure 7 has negative torque values. Recalling that the amplifier and transmitter circuitry is designed to pass a dynamic signal, the DC value is attenuated and high pass information remains. The same effect is recreated in the model output by passing a 4th order high pass Butterworth filter over the simulated torque data. As with the experimental signal, the model FIR filter was given a corner frequency of 10 Hz. In this way, the dynamic torque signal is found to be nearly identical in all features (with the exception of magnitude) to the simulated dataset.

3.2 Cut testing

To experimentally evaluate the transmitter, tests are conducted with parameters similar to the model validation experiment. However, these tests were conducted alongside a bed mount dynamometer. Using the torque sensor integrated tool, a measured comparison can be made between the output of the transmitter and the force output of the bed dynamometer sampled at 20 kHz. Although the bed dynamometer does not provide a direct measurement of torque, the force in *X* or *Y* directions can be used to calculate the moment supplied by the tool. This is done in a half-immersion cut where the tool completely exits the material and reengages the material with the cutting edge tangent in the *X* direction. The moment is then estimated by knowing the impact force in the *X* direction at the tool radius of 0.009525 m (0.375”). The impact torque from the sensor system is measured as a voltage signal. By a ratio of this peak voltage signal to the peak estimated torque, the voltage signal can be scaled. Figure 8 shows the voltage signal from the sensor integrated tool after being scaled by this technique.

Figure 8 Calibrated dynamic torque signal (see online version for colours)



It is found that the scaled torque signal from the sensor-integrated tool is in agreement with the magnitudes predicted by the cutting force model (Figure 7). This suggests that output from the wireless tool holder is reasonable and useful for observing the magnitude of dynamic torque. This agreement also supports the effectiveness of the bed dynamometer sensitivity analysis for approximating torque supplied by the tool. Furthermore, a comparison can be made between the resolved *XY* bed force and the torque. This contrast confirms that the duration of engagement with the workpiece is correctly determined by the torque signal. Figure 9 illustrates the resolved bed force and dynamic torque. Since the natural frequency of the bed dynamometer is approximately 1000 Hz, frequency content above 400 Hz has been attenuated in the signals shown in Figure 9.

In addition to collecting force values from the bed dynamometer, spindle power data was also collected at 20 kHz. Figure 10 shows output from both the wireless torque sensor and the spindle load cell.

It is immediately obvious that the power sensor has a lower dynamic bandwidth than the wireless torque sensor tool. The power sensor was over sampled to expose the large amount of high frequency noise present in the power signal. The superiority of the wireless torque signal to the power sensor is apparent in both resolution and signal to noise ratio. However, the power sensor specialises in sampling frequency content below the 10 Hz cut off of the dynamic torque signal, including the DC component.

Figure 9 Dynamic torque vs. resolved bed force (see online version for colours)

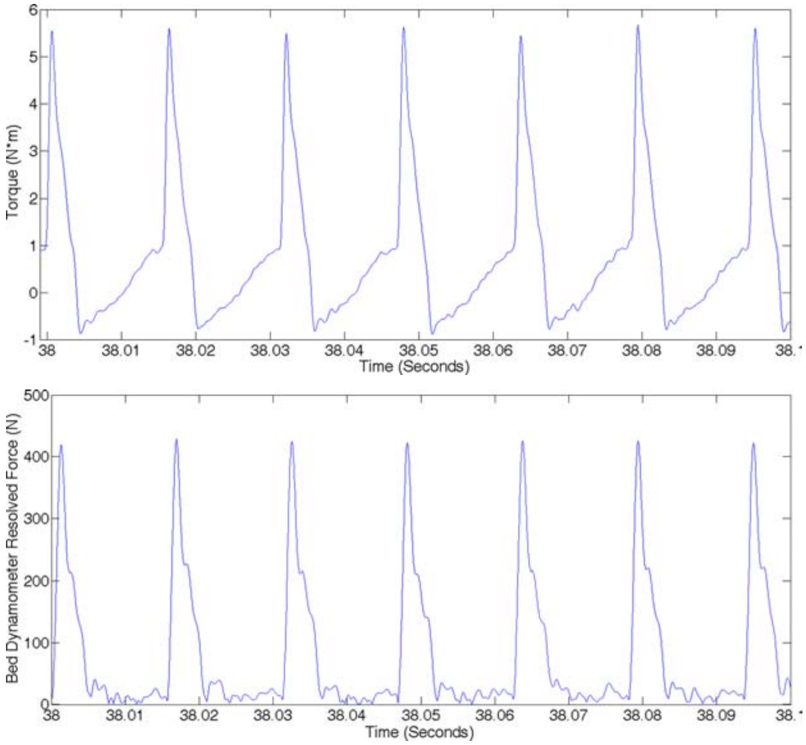
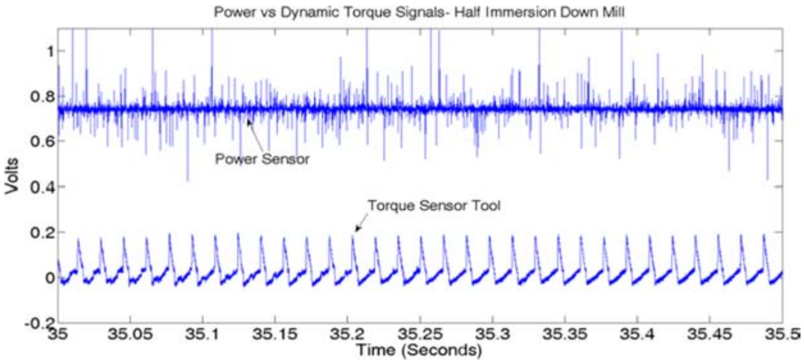


Figure 10 Spindle power vs. dynamic torque (see online version for colours)



4 Current and future work

The sensor transmitter system developed in this work is the first reduction to practice of multi-channel wireless techniques for recording sensor-integrated tools. The successful results have created fertile ground for further development, design evolution and application.

4.1 A dynamic dilemma: current work to transmit DC

The weakness of the transmitter solution described in this paper is its inability to transmit extreme low frequency <10 Hz or DC signal components. For many dynamic milling phenomenon such as chatter and runout, this is acceptable (Suprock et al., 2008a). However, for real time force model calibration and wear monitoring, it is critical to understand the mean torque. For this system to be a more complete sensor solution for end milling, DC signal is a requirement.

To satisfy the need for low frequency and DC signals, further development is conducted. First, the Bluetooth audio transmission protocol is evaluated for its applicability to DC signals. Since the A2DP protocols were intended for passing dynamic audio, the transmitter hardware is constructed to stop low frequency content. This is accomplished by an analogue high pass filter located before the A/D. Although the signal is filtered, it is presumed that the A/D will accept and encode any DC signal within its quantisation range.

As expected, the Com One stereo transmitter contains an analogue bandpass filter from 10 Hz to 20 kHz. After this filter is circumvented, it is discovered that the frequency response of the transmitter continues to attenuate a DC signal. Unfortunately, this was anticipated since many audio bandwidth A/D chips contain a default digital or analogue filter to attenuate DC components in the signal.

To test the hypothesis that the Com One audio A/D contains a built in DC filter, a lower cost Bluetooth headphone transmitter is dissected and the pre-A/D analogue filter is removed. It is expected that in a lower value A/D, no DC blocking feature is present. The transceiver board from a Jabra BT135 personal microphone headset (approximate retail cost $8) was chosen for this experiment. This transceiver was designed to accept a resistive load from an electret condenser microphone. The unit is altered to sample a voltage signal for testing. After this modification, the circuit is not operating within specification and must be re-evaluated for functionality and performance.

Because the modifications are intended allow DC to pass, the first signal tested on the modified Bluetooth transmitter is a 1 Hz square wave. It is observed that the zero reference of the modified circuit was 0.7 volts with a dynamic range of ±150 mV. The bandwidth of the modified headset transceiver is 0–3250 Hz. This is sufficient for observing the entire dynamic range of interest and indicates that a commercially available Bluetooth audio transceiver can be modified to transmit DC signals.

4.2 Future work

This research will continue to develop the sensor integrated tooling technology, with a specific focus on the application of DC wireless transmission over Bluetooth protocols such as A2DP. The use of the Bluetooth standard is valuable since the technology has been adapted for mass production and is low in cost. With the deployment of DC modified transmitters, tool tip temperature sensors are also being developed.

Application-based work is under way to find practical uses for a low cost rotating sensor system. Immediate applications in tool wear monitoring exist since a high resolution replacement for spindle load cells allows a more accurate description of tool health.

5 Conclusion

The goal of this work is to evaluate the methods and test the feasibility of using the A2DP transmitter to send a signal from a sensor integrated tool. The results are encouraging and show that it is possible to record a torque signal with good signal to noise ratio. A high bandwidth stereo transmitter for sensor integrated tooling has been successfully designed and demonstrated. The Bluetooth A2DP audio profile is acceptable for transmitting end milling sensor data. The system has shown excellent response and bandwidth capabilities to 17 kHz, which exceeds the requirements for typical end milling sensor data.

A torque sensor-integrated tool has been developed that does not increase the compliance of the milling system. The transmitter system has been tested with this tool and experimental data is collected from cutting tests. To validate the signal shape, the experimental torque signal is compared to a mechanistic cutting force model. The signal highly reflects expected physical behaviour during cutting, shown by this comparison to a cutting force model. Traditional sensors also confirm that the torque signal makes physical sense and is of high quality. Experimental comparisons are made to a bed type dynamometer and spindle load cell.

Because the dynamic torque signal transmitted by the A2DP interface lacks the DC signal component, a solution is described and tested. As an example, a commercially available Bluetooth headset transceiver was modified to allow a 0–3250 Hz passband- satisfying the need for DC signal.

This work is an exciting step towards satisfying industrial requirements for a sensor-integrated tooling system. A practical sensor integrated tooling system can be developed using the methods described in this paper (Suprock, 2008).

Acknowledgement

Study Conducted in Affiliation with the University of New Hampshire.

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