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Battery-free Digital Tooling Head using Wireless Power Transmission

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ABSTRACT

This study demonstrates a battery-free digital tooling head (BF-DTH) for real-time monitoring of a rotating machine tool. As tooling heads include more digital electronics and consume more power with improved functionalities, replacement and management of batteries become major issues. A BF-DTH using wireless power transmission is proposed to resolve these issues. The BF-DTH is composed of a transmitter/receiver (TX/RX) coil pair, converters, a wireless microcontroller and thermal sensor. The microcontroller, powered by a wirelessly transmitted and converted DC voltage, measures the tool's temperature and continuously transmits data from the rotating BF-DTH to an external wireless terminal. The delivered RX power was measured to be 32 mW at 15% efficiency, with the RX converter providing a constant DC voltage regardless of spindle speeds of up to 1200 RPM. The BF-DTH system could be effectively used for emerging smart factory applications, where smart DTHs consume moderate to high power.

1. Introduction

Conventional machine tools employ a tooling head to provide interface between the spindle and cutting tool. The tooling head is mounted on the spindle either manually or automatically as shown in Fig. 1(a). Some tooling heads, for example, a boring head, include a function to manually adjust the tool's position by reading the scale of a mechanical vernier embedded in the head [1]. Several companies have recently introduced a digital tooling head (DTH), embedding digital electronics and LCD-displays to improve readability and accuracy. A wireless terminal (smartphone or tablet) can followingly be connected to the digital readings, optimizing cutting parameters and logging historical adjustments as shown in Fig. 1(b). The DTHs are more accurate, efficient and convenient than the traditional heads, but are powered by a battery and potentially consume more power due to the digital electronics including wireless communication functionalities (Fig. 1(b))[2]. This increased power consumption results in more frequent battery charges and replacements. Some machine tools employ multiple tooling heads with a tool changer to mount different cutting tools depending on the machining process (Fig. 1(a)). This issue makes the battery management in DTHs even more challenging and can lead to a reduced productivity or increased manufacturing costs. Some researchers have therefore proposed a battery-free wireless sensor for a rotating object using RFID technology [3]. Nevertheless, this approach is mainly for low-power devices (tens of micro-watts) and has the limitation that transmitted RF power is usually not sufficient to drive various sensors or electronics, consuming moderate to high power (tens of milli-watt). Additionally, the number of sensors and electronics in a DTH are likely to increase further with the emergence of smart manufacturing, enabling further

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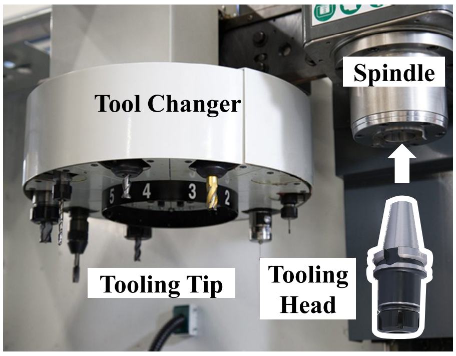


(a) General tooling head and spindle (Haas Automation Inc.)

(b) Digital tooling head (KAISER Inc.)

Fig. 1 Conventional tooling heads [1,2]

monitoring of tool conditions and machining processes.

To resolve the battery issue and to engage higher power consumption in a rotating spindle, a wireless power transmission (WPT) system consisting of multiple transmitters and receivers was proposed for a rotating large steel spindle [4]. Some WTP systems for a rotating spindle employed coaxial (concentric) coils due to their simple configuration [5-8].

A battery-free digital tooling head (BF-DTH) using the coaxial coil WPT is proposed and implemented in this paper. The architecture of the BF-DTH system is designed and analyzed to power electronic devices mounted on a rotating tooling head. A prototype is implemented to show that the BF-DTH can measure time-varying temperatures of a rotating tool and transmit the data to an external wireless terminal.

2. Design

The architecture of the proposed BF-DTH system is shown in Fig. 2. The system is composed of two parts: the stationary part, installed on the spindle stator, and the rotary part, mounted on the rotating tooling head. The TX converter, seen on the stationary part, converts a DC input voltage from the

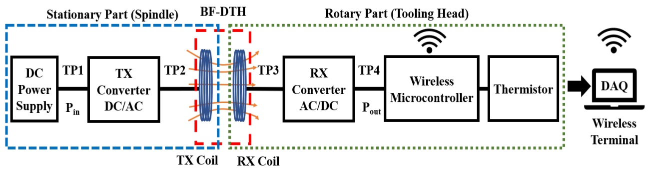


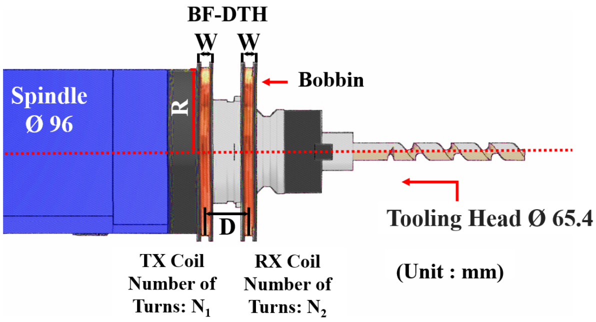
Fig. 2 Block diagram of battery-free digital tooling head (BF-DTH)

DC power supply to an AC voltage, exciting the TX coil. Due to inductive coupling, an AC voltage is induced in the RX coil which can followingly be converted by the RX converter to a DC voltage, powering the wireless microcontroller. A thermal sensor (thermistor) connected to the microcontroller then measures the temperature of the cutting tool, after which the obtained data is wirelessly transmitted to a wireless terminal outside for data acquisitions. Since a simple back-to-back coaxial (concentric) coil configuration is employed, the geometry of the RX coil does not change during tooling head operation. The TX/RX coils achieve a constant magnetic coupling to transmit a constant power regardless of the angular position or the rotational speed of the BF-DTH. Further indications in Fig. 2 include: TP1, TP2, TP3 and TP4 representing test points to monitor voltage waveforms using an oscilloscope and P_{in} and P_{out}, the input and output power of the TX and RX converter, respectively.

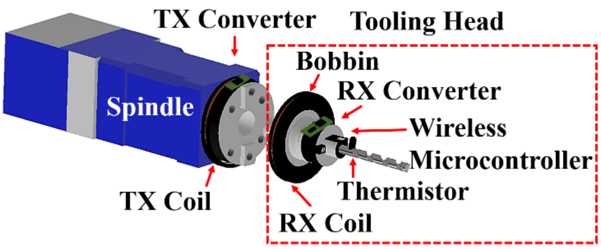
A commercial WPT module (EF03089) is installed as TX/RX converter, a 6000-RPM 1.5-kW Spindle/Motor (BT-30) functions as the platform and a BT-30-type collet chuck (BT-30-ER-16) is selected as tool head [9]. Lastly, a Wi-Fi microcontroller (ESP8266/CP2102) carries out the wireless data transmission, completing the assembly.

Fig. 3 shows the design of the proposed BF-DTH system with assembly of the selected components. The TX/RX coils are each wound around a plastic bobbin and mounted on the spindle and tooling head, respectively, as shown in Fig. 3(a). A drill bit with attached thermistor is additionally installed to the configuration, functioning as the cutting tool. Fig. 3(b) shows the placement of the TX/RX coil pair having a common coil inner radius, R, and width, W, held by the bobbin structure. The pitch between the centers of the TX/RX coils is followingly indicated as D.

Table 1 lists the coil pair design parameters, adapted to fit the selected spindle geometry as described before. The coils are made out of copper wires with the diameter of 0.5 mm, W of 5 mm, R of 49.5 mm, slightly larger than the spindle head, and D of 10 mm, the minimum value considering



(a) 2D schematic drawing



(b) 3D schematic drawing

Fig. 3 Design of the proposed BF-DTH system

Table 1 Design parameters for TX/RX coils

Parameters	Value
Coil wire diameter	0.5 mm
Coil inner radius (R)	48.5 mm
Coil width (W)	5 mm
Coil pair pitch (D)	10 mm
TX Coil - Number of Turns (N_1)	13.5
RX Coil - Number of Turns (N_2)	12

physical implementation issues. D is here minimized to allow for a maximum mutual inductance and power transmission efficiency [10]. The employed TX/RX coils can be described as a typical coupled coil pair and modeled with the equivalent electric circuit on Fig. 4. Self-inductance and resistance of the pair are indicated as L_1/L_2 and R_1/R_2, respectively, with M as the mutual inductance between the two coils [11,12]. The TX/RX converters should be combined with a 30 μH-inductor as per specification, therefore requiring both L_1 and L_2, indicated on Fig. 5, to be designed accordingly. To satisfy this self-inductance requirement ($L_1 = L_2 = 30$ μH), an LCR meter (Keysight U1733C) was used while changing the number of turns in both TX and RX coil, N_1 and N_2, respectively. The required inductance was finally experimentally obtained when $N_1 = 13.5$ turns and $N_2 = 12$ turns, as summarized in Table 1.

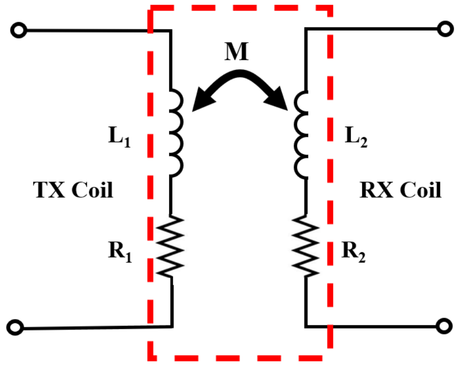
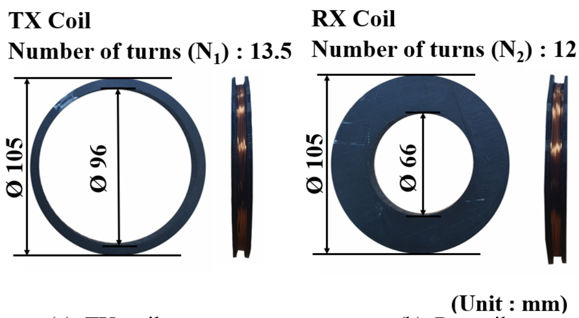


Fig. 4 Equivalent circuit of the TX/RX coils



(a) TX coil (b) Rx coil

Fig. 5 Manufactured TX/RX coil

3. Experimental results

The previous section went over the design process of the presented BF-DTH system, allowing for all components to now be followingly implemented in a functioning prototype. The TX/RX coils were manufactured according to the specifications shown in Fig. 5, having their plastic bobbins made with 3D printing.

The wireless microprocessor (ESP8266/CP2102) is powered by the RX converter TP4 output and fitted with a 10 kΩ-thermistor (NTC - 10KD-5J), allowing for a real-time temperature monitoring of the drill bit. Fig. 6 and Fig. 7 shows the implemented prototype and the close-up view of the detail component configuration of the BF-DTH system, respectively.

Table 2 shows the measured circuit parameters of the TX/RX coil pair as indicated earlier on Fig. 4. The inductances of the pair, L_1 and L_2, were measured directly at 100 kHz using the LCR meter, while the mutual inductance, M, was measured using a differential-cumulative method [14]. The obtained L_1 and L_2 values are quite close to the self-inductance requirement of 30 μH, as laid out in Section 2.

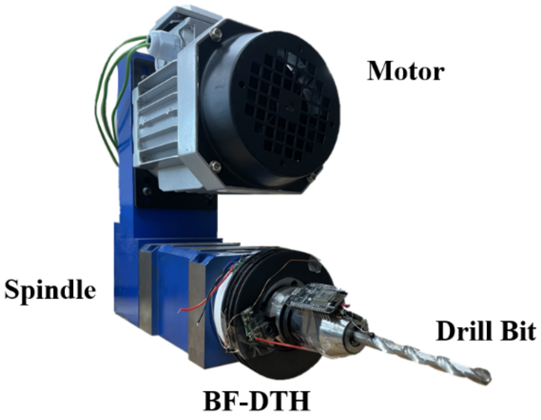


Fig. 6 BF-DTH system installed on the machine tool

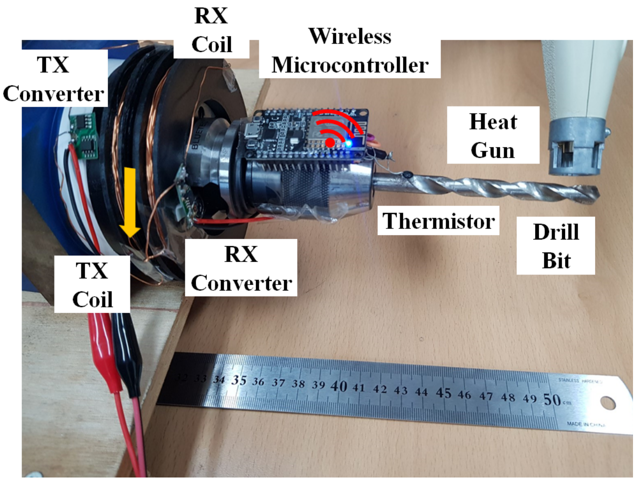


Fig. 7 Detail components configuration of BF-DTH system

Table 2 Measured equivalent circuit parameters of the TX/RX coils

L_1 (μH)	L_2 (μH)	M (μH)	R_1 (Ω)	R_2 (Ω)
32.0	29.6	8.6	1.8	1.6

Fig. 8 shows the complete experimental setup. A thermal cycle is intermittently applied to the drill bit using a heat gun (Weller 6966C) at 3 cm distance, having the spindle set to a moderate speed of ~600 RPM. The spindle speed is measured using a conventional tachometer. The heat gun is turned ON for 5 secs and OFF for 15 secs, repeatedly. The measured data is wirelessly transferred from the microcontroller (mounted on the rotating spindle) to the wireless terminal outside.

The voltage waveform in each system test point (TP1-4), as indicated on Fig. 2, is measured using an oscilloscope (Keysight MSOX4024A) and followingly displayed on Fig. 9. A 12 V-DC voltage from the DC power supply is applied

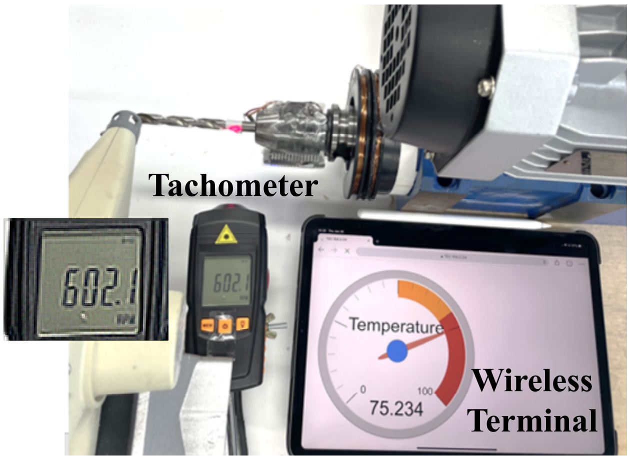


Fig. 8 Experimental setup for testing BF-DTH system

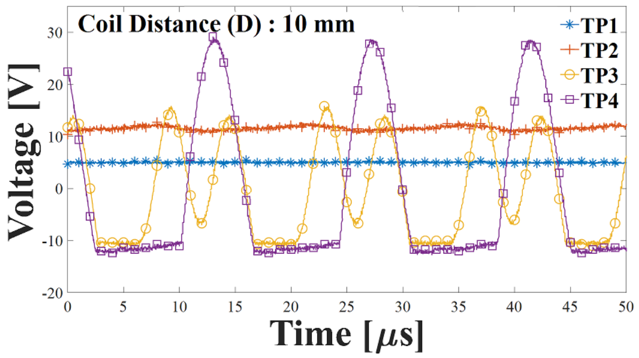


Fig. 9 Measured voltage waveform at each test point (TP1-4)

to the TX converter (TP1) after which a 69.6 kHz AC voltage in TP2 and TP4 is measured of 48 and 20 V peak-to-peak, respectively. The output voltage of the RX converter (TP4) is measured to be 5 V-DC as per specification.

The input power (P_{in} of TX converter), output power (P_{out} of RX converter) and the power transfer efficiency (P_{out}/P_{in}) are followingly estimated using the measured voltage waveforms in Fig. 9. P_{out} additionally needed the use of a small resistor (5 Ω) connected in series to estimate its output current. P_{in} and P_{out} are accordingly measured to be 214 and 32 mW, respectively, resulting in a 15% power transfer efficiency at a coil pair distance (D) of 10 mm. P_{out} and transfer efficiency are verified with increasing pitch, as shown in Fig. 10. The efficiency is seen to be dropping from 15% to 9% as p increases from 10 to 20 mm.

Additionally, the RX converter should be able to provide a constant DC voltage regardless of BF-DTH rotation speed. The output voltage of the RX converter (TP4 voltage) is verified for various spindle speeds up to 1200 RPM as shown in Fig. 11. The measured DC voltage is found to be close

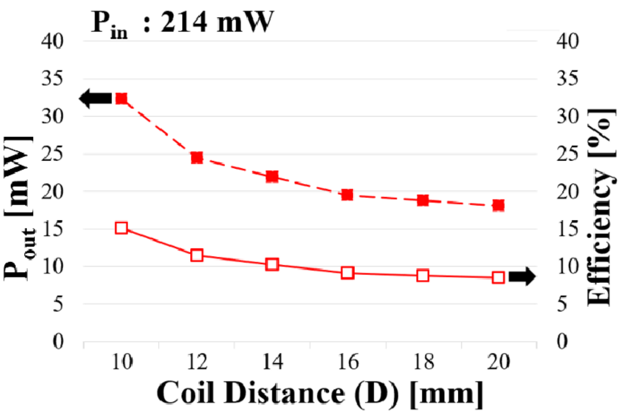


Fig. 10 Measured input and output power and efficiency with varying coil pitch (D)

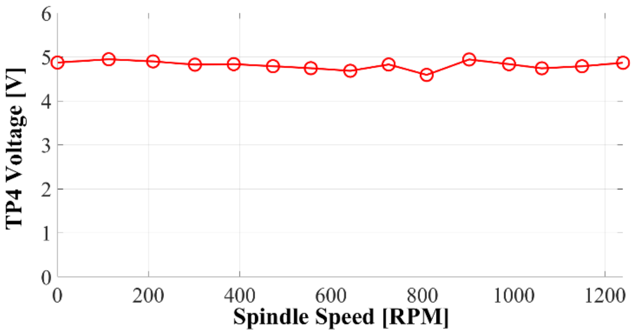


Fig. 11 Output DC voltage of the RX converter (TP4) with varying spindle rotational speed

to 5 V, as required per specification, with only slight variations accounting to less than 10%. The results clearly show that the transmitted power is only slightly, to not affected by the radial position or speed of the BF-DTH.

Lastly, Fig. 12 shows the time-varying temperature of the cutting tool by cyclic heating of the drill bit at a rotational speed of 600 RPM, as described earlier. The display interface on the wireless terminal shows a temperature gauge, enabling real-time monitoring of temperature changes as observed by the thermistor-microcontroller assembly. No connectivity issues in the wireless data transmission were observed for the spindle speed lower than 1200 RPM. The spindle speed has not been raised further due to a safety issue. The BF-DTH system is expected to work at even higher spindle speeds.

4. Conclusion

This paper demonstrated a battery-free digital tooling head (BF-DTH) for real-time temperature monitoring of a rotating

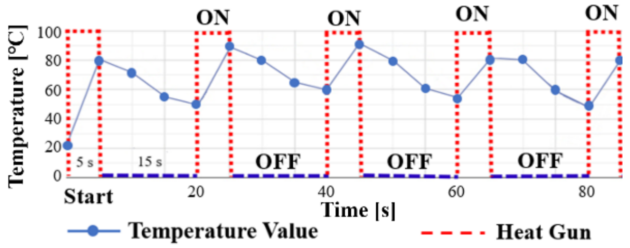


Fig. 12 Time-varying temperature of the rotating cutting tool measured by the BF-DTH system at the spindle speed of 600 RPM.

machine tool. For the first time, the WPT technology has been applied to supply digital electronics in a rotating tooling head with moderate to high power without a battery. The BF-DTH architecture is proposed and implemented using a real spindle and tooling head. The temperature is successfully measured and transmitted to a wireless terminal up to a maximum spindle speed of 1200 RPM. The transmitted DC power is measured to be 32 mW with a power transfer efficiency of 15%. The RX converter generates a constant DC voltage throughout the speed range. The time-varying temperature of the rotating cutting tool is also measured through cyclic heating of the cutting tool. Smart factories need smarter DTHs with more sensors and electronics to monitor tool conditions or processes for predictive and preventive maintenance [15]. The proposed BF-DTH system would be effectively applied to smart DTHs which consume moderate to high power.

Acknowledgement

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