Simultaneous Wireless Power and Data Transmission Over One Pair of Coils for Sensor-Integrated Rotating Cutter

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ABSTRACT Tool condition monitoring is becoming particularly important in the cutting process. More and more researchers start to integrate the sensors into the tool holder due to its convenient use and wide applicability. However, it is difficult to transmit out the condition data and supply stable power to the sensor-integrated systems through the traditional wired way as the tool holder is under high-speed rotation in milling or drilling process. In this paper, a novel simultaneous wireless power and data transfer system over one pair of coils for sensor-integrated rotating cutter is presented, and the eddy effect caused by the metal handle that impacts the system performance is solved with ferrite shielding. To transmit out the cutting condition data wirelessly, the synchronous detection and envelope detection technology are employed. Meanwhile, the synchronous rectification technology is adopted to improve the performance of the wireless power transfer.

INDEX TERMS Tool condition monitoring, rotating cutter, simultaneous wireless power and data transfer, one pair of coils, ferrite shielding.

I. INTRODUCTION

Cutting tool plays a vital role in the cutting process, whose abnormal changes directly affect the machining accuracy and workpiece surface quality [1]–[3]. Thus, monitoring the tool cutting conditions, such as cutting force [4], torque [5], vibration [6], and temperature [7], is becoming particularly important, and thus has recently aroused great concerns from both academia and industry. Traditionally, wires are needed in a tool condition monitoring system to transmit out the cutting condition data to a host computer. High costs, troublesome installations and low reliability are often the disadvantages of using these wired systems. Besides, as more and more researchers start integrating different types of sensors and the relevant signal processing circuits into the tool holder to obtain the conditions in the positions near the cutting zone, then there would exist a great challenge to transmit out the condition data and supply sufficiently stable power to the sensor-integrated systems through the traditional wired way when monitoring the rotating cutter with a high speed in milling or drilling process. Hence, the development of a suitable power and data transfer system for the sensor-integrated rotating cutter is of great significance.

Due to the limitations of current wired sensor systems, and in order to reduce the invasion degree of sensor system into the milling or drilling process and increase flexibility, a series of wireless sensor-integrated systems for rotating cutter have been developed [8]–[23], in which the sensors and other electronic components, such as sensor signal processing module, wireless data transfer module, and power supply module, are all integrated into the tool holder. For the key wireless data transfer module, the common technologies, namely Bluetooth [8]–[11], ZigBee [12]–[14], WiFi [15]–[20], Radio frequency identification (RFID) [21] and sub-1 GHz
radio frequency [22], [23], have been adopted to transmit the measured condition data wirelessly to a upper host computer. It can be noted that WiFi is the most widely used transmission method for tool condition monitoring, which has the potential to be a competitor of other wireless transmission technologies taking into account of its relatively high transmission speed and long transmission distance. Unfortunately, the power consumption is a little high, thus bringing a high request to the power module.

Among the above wireless sensor-integrated systems, the power modules are basically achieved using different types of battery, including the ordinary or rechargeable battery in view of its convenient use [24]. However, the batteries have only a limited lifetime, and increase the system volume. In addition, when the batteries are exhausted, recharging or replacing them is an expensive and difficult task. Therefore, some researchers started to utilize the energy harvesting techniques [25], [26] for powering wireless sensing systems in rotating applications. Particularly, in the application of rotary tools, Chung et al. [14] presented an attachable electromagnetic energy harvester to power the wireless vibration-sensing system, in which four magnets on the rotating spindle in milling processes make a coil induce currents to provide the required electrical energy output. However, this output energy is only enough at the spindle speed of over 1650 rpm, which undoubtedly restricts its applications. Besides, another new solution by Ostasevicius et al. [22], [23] proposed a piezoelectric energy harvester to convert the energy of mechanical vibrations into electrical energy in the turning and milling process, respectively. However, the frequency bandwidth is relatively narrow.

As the mainstream technology in power supply to the battery-less systems, the wireless power transfer technology based on electromagnetic coupled resonance or inductive coupling has been applied to the embedded sensors on rotating spindle [27]–[29]. There are multiple transmit and receive coils for much more stable power delivery and higher transfer efficiency. As the coils are attached on the rotating shaft and mounted on the fixture, respectively, this, however, would result in a large volume with the invasion of machining environment. Furthermore, in these wireless power transfer systems, only power transfer is not enough, so it is necessary to add the data transfer link. The existing data transfer methods mainly include adding an additional data transfer module and simultaneous transfer of power along with data. Compared with ZigBee [29], Bluetooth and other data transfer modules, simultaneous transfer of power along with data has the advantages of high speed, high stability and no additional circuit, which has been widely used in the biomedical applications [30]–[32]. Not only that, this technology has also been employed by Rizal et al. [33]–[35] for tool condition monitoring of rotating cutter, in which a pair of inductively coupled coils are added to an inductively coupled power transfer system to transmit the cutting data. It can be seen that there are two inductive near-field links to transfer the power and cutting data separately using two pairs of coils. Therefore, if the power and data transfer in tool condition monitoring share the same inductive link between only one pair of coils, the complexity of system design and implementation can be reduced apparently, and the reliability and anti-interference ability can be improved greatly. However, to the best of the authors’ knowledge, there has not been a solution using wireless power and data transfer systems for condition monitoring of sensor-integrated rotating cutter.

Considering the advantages and potential of the wireless sensor-integrated systems, this paper makes a contribution in addressing the issues, dealing with the design and construction of a wireless power and data transfer system over one pair of coils for sensor-integrated rotating cutter, which is capable of transmitting the cutting condition data and supplying stable power in milling or drilling process. This proposed wireless system consists of a standard tool holder, wireless power and data transmission module, integrated sensors, and other related electrical circuits. First, the scheme design, including the overall structure, system parameter and implementation scheme, is expounded. Then, system implementation is presented in detail. Finally, a milling experiment of aluminum bar is proposed to verify the performance of designed power and data transfer system. Even though this system is designed for rotating cutter, it can also be applied in other rotating devices to transmit out the condition data wirelessly. Thus, it has a wide range of applications.

II. SCHEME DESIGN

A. OVERALL STRUCTURE

Figure 1 shows the overview of the wireless power and data transfer system for sensor-integrated rotating cutter, which is used to supply power for the whole system, and transfer the cutting condition data to a host computer wirelessly over one pair of coils. There are two coils connected to the transmitter end and receiver end, respectively. As the tool
holder is under high-speed rotation, the installation of these devices is a problem worthy of attention. Firstly, the circuit board of the transmitter end is fixed on the stationary tool body and the transmitter coil is embedded in a customized holder that still connected with the tool body. Thus, when the cutting tool rotates, the circuit board and coil of transmitter end can remain stationary. At the same time, the circuit board and corresponding coil of the receiver end are fixed on the cutter shank, which can rotate coaxially with the tool cutter. Therefore, the relative rotation of the transmitter end and receiver end is realized, and the problem that the cutting condition data of rotating cutter are difficult to transmit out through the traditional wired way can be solved.

B. SYSTEM PARAMETER
For easy integration of the two coils and rotating cutter, the coaxial structure illustrated in Figure 2 is adopted. As the coils are loosely coupled with low coupling coefficient, it is necessary to optimize the system parameters. Based on the analysis and research of optimization design in our former paper [36], the main parameters of the two coils include the spacing between the coils $d$ and the inner diameter of the coils $r_0$, which are set to be 4 mm and 20 mm, respectively. Besides, considering the transfer efficiency, load receiving power, carrier frequency requirements of the wireless data transfer, an appropriate system working frequency of 200 kHz is selected. According to the relative permeability and conductivity of the coil material, it can be obtained that the skin depth of the coil is 0.148 mm at the working frequency of 200 kHz. Therefore, the litz wire, whose diameter of single strand is 0.1 mm, and 20 strands in total is adopted to wind the coils.

![Coaxial structure of the transmitter coil and receiver coil.](image)

III. SYSTEM IMPLEMENTATION
A. OVERCOMING THE EFFECT OF METAL HANDLE ON SYSTEM PERFORMANCE
According to Faraday electromagnetic induction principle, there would be a large number of induced eddy currents on the surface of the conductive metal handle, which can be analyzed though ANSYS Maxwell software. This adverse effect named as eddy current effect can consume plenty of electrical energy in the wireless power transfer process and reduce the power transmission efficiency [38]. A simple and effective solution to alleviate the eddy current effect caused by the metal handle is the ferrite shielding, which uses high-permeability and low-conductivity ferrites to provide low reluctance paths for the magnetic flux lines of the two coils so as to suppress the production of eddy currents [39], [40]. Figure 3(a) and Figure 3(b) show the schematic diagram and physical map of the tool handle with ferrite shielding.

![Tool handle with ferrite shielding.](image)

C. IMPLEMENTATION SCHEME
At present, the wireless power transfer based on inductive coupling or electromagnetic coupled resonance is relatively mature. Considering that the self-resonance coupling coils of electromagnetic resonance works at a high frequency of MHz level, it is required that the length of coils should be higher than half of the electromagnetic wave length [37], which thus makes the size of the coils larger. However, the space of cutter shank is narrow and the installation position is limited. Therefore, it is not conducive to integrate the coils with the tool holder. At the same time, inductive coupling wireless power transfer technology has been widely used with simple implementation. Although its transmission distance is short, fortunately, not long-distance wireless power transfer is required. Thus, using inductive coupling wireless power transfer technology in sensor-integrated rotating cutter is appropriate.

For the wireless power transfer, it consists of transmitter end, receiver end and coupling coils. The transmitter end converts DC signal into high frequency AC signal through the inverter circuit, which can induce AC signal on the receiver coil by the magnetic field. Then, a DC voltage can be obtained by rectifying and filtering at the receiver end, which is used for load after a power processing module.

Meanwhile, wireless data transfer is realized by near-field coupling. In this case, the basic principle of wireless data transfer and power transfer are all based on Faraday electromagnetic induction, which can be implemented in a same hardware system. Therefore, doing so can make the structure of wireless power and data transfer system simple, reduce the size and cost of the hardware, and is conducive to system miniaturization and integration.
can be calculated as follows:

\[ k = \frac{V_2}{\omega I_1 \sqrt{L_1 L_2}}. \]

Here, \( L_1 \) and \( L_2 \) are the inductances of the transmitter and receiver coil, \( \omega \) is the angular frequency, \( V_2 \) is the voltage amplitude on the receiver coil, and \( I_1 \) is the current amplitude on the transmitter coil. Table 1 shows the measured coupling coefficient \( k \) with different spacing in three environments. It can be found that the handle can seriously reduce the coupling coefficients, and by adding the ferrite shielding, the coupling coefficients increase by about 32.84% than that with the tool handle, and about 13.4% comparing with the values in the air. In addition, with the increase of spacing between the two coils, the coupling coefficients in three environments all show a monotonic decreasing trend, which is consistent with the theoretical results.

**TABLE 1. Coupling coefficient of coils with different spacing in three environments.**

| Spacing (mm) | Air   | Tool handle | With ferrite |
|--------------|-------|-------------|--------------|
| 3            | 0.6236| 0.5381      | 0.6753       |
| 4            | 0.5716| 0.5183      | 0.6483       |
| 5            | 0.5431| 0.4666      | 0.6153       |
| 6            | 0.509 | 0.4031      | 0.5701       |
| 7            | 0.4629| 0.3957      | 0.5553       |

**B. WIRELESS POWER AND DATA TRANSFER**

Simultaneous transfer of power along with data based on the near-field inductive coupling is employed to transmit power from the transmitter end to receiver end, and transmit data in both directions for the rotating cutter, as shown in Figure 4. The transmitter end mainly includes power supply module, microcontroller, full-bridge inverter, data modulation and demodulation module, and series resonant coil. The receiver end mainly includes the series resonant coil, full-bridge rectifier, data modulation and demodulation module, voltage conversion module, and microcontroller. The blue flow line represents the process of transmitting power from the transmitter to receiver, and the measured condition data from the receiver to transmitter.

1) WIRELESS POWER TRANSFER

The receiver needs to convert the AC signal on the receiver coil into the DC signal through the rectifier circuit. Its conversion efficiency can improve the power transmission efficiency, so the rectifier circuit of the receiver is very important. However, when using the traditional diode full-bridge rectifier, shown in Figure 5(a), each diode has a fixed voltage drop of about 0.6V, and consumes a larger power, which can generate a higher power loss. To solve these problems, the synchronous rectifier with the MOSFETs is usually applied. The MOSFET has minimal on-resistance, and its voltage drop is much lower than that of the diodes, thus reducing the power loss. In this paper, four N-MOSFETs are used to design the full-bridge synchronous rectifiers so as to improve the power transmission efficiency as much as possible. Figure 5(b) shows the structure of the synchronous rectifier. During the working process, the Q1 and Q4 are turned on or off simultaneously, as are the Q2 and Q3. In this case, the AC signal of coil is input from the L+ to L−, and the rectified signal is output from the Vrect to PGND. This control strategy can prevent the direct current flowing from Vrect to PGND that can lead to the damage of the MOSFETs. Meanwhile, the switching sequence of the MOSFETs needs to be synchronized with the input AC signal. Therefore, it is usually necessary to detect the change of the AC input signal, and generate the control signal to drive the MOSFETs.

The synchronous rectifier chip UCC24610 of TI with the leak-source voltage sensing technology is adopted, which can select the switching time of the MOSFETs by comparing the leak-source voltage with the internal switching threshold \( V_{\text{THON}} \) and \( V_{\text{THOFF}} \), making no need to design the AC signal detection circuit and the corresponding control program.

2) WIRELESS DATA TRANSFER

Compared with the other modulation methods, the ASK (Amplitude Shift Keying) modulation by adjusting the loop voltage has the advantages of simple implementation, and constant carrier frequency, which can have no influence on
the resonance of wireless system. So, the ASK modulation is employed in the transmitter to send the data to the receiver. Meanwhile, the load modulation by adjusting the load resistor is adopted in the receiver to return the data to the transmitter, which has already been widely applied in the RFID system and the Qi standard for wireless charging. The ASK modulation circuit of the transmitter and load modulation circuit of the receiver are simple to realize, which are not listed here.

The receiver needs to send a large amount of condition data to the transmitter. In order to ensure the normal pick-up of power at the receiver, the smaller the modulation depth at the receiver, the better. In this case, the amplitude of the induced voltage on the transmitter coil would change very little. So, the synchronous detector with better anti-noise ability is a good choice for the demodulation circuit of the transmitter. Figure 6 shows the synchronizing demodulation circuit, in which the modulation signal Demod is from the transmitter coil, and the local carrier signal is the PWM (Pulse Width Modulation) control signal of the full-bridge inverter. First, the PWM signal is multiplied by the modulation signal. Then a low-pass filter is used to remove the high-frequency signal, and a high-pass filter is also employed to filter the low-frequency and DC signal. The obtained signal is amplified and converted to a digital signal by a hysteresis comparator. Finally, through a level conversion circuit, the signal is input into the microcontroller.

Due to the high modulation depth of the ASK signal at the transmitter, good demodulation performance can be achieved by using both the synchronous detector and envelope detector for the receiver. Considering that the receiver rotates with the cutter handle, so the envelope detector with fewer components, as shown in Figure 7, is more practical, which includes only a basic RC circuit and a diode. A low-pass filter and a high-pass filter are adopted to remove the high-frequency and low-frequency noises in the envelope detection signal. Finally, the signal is input into the analog comparator MCP6561 to get the demodulated signal.

IV. EXPERIMENTAL RESULTS
A. EXPERIMENTAL PLATFORM
1) TEMPERATURE MEASUREMENT WITH INTEGRATED THERMOCOUPLE
As an illustrative example of the sensor data source, the cutting condition of temperature is employed to verify the performance of designed power and data transfer system. So far, several methods have been proposed to sense the cutting temperature, such as the infrared imaging [41], integrated thermocouple [42], optical fiber [43], [44] and thin-film thermocouple [45]. Among these methods, the integrated thermocouple is simple in construction, low in cost, and easy to realize. Thus, the most used K-type thermocouple is selected.
to measure the cutting temperatures of rotating cutter, which needs to be integrated into the cutting tool. To get more accurate cutting temperatures, two mounting holes with the diameter of 1 mm are positioned close to the corner and on the cutting face, see Figure 8. Then the thermocouple is packaged in the mounting hole with high temperature resistant insulating adhesive. This integration has the advantages of simple structure and low cost, which make it easy to manufacture.

2) PLATFORM INSTALLATION

Based on the above system implementation, the circuit boards of the receiver and transmitter end are realized, as shown in Figure 9(a) and Figure 9(b), respectively. The former is designed to be circular, which is easy to install and fix on the cutter shank. Then, considering the size of the circuit boards and the installation of the two coils, the cover and coil holder are designed and fabricated by the 3D printer, as shown in Figure 9(c). With the boards and coils installed into a rotating cutter, an experimental platform of the designed wireless power and data transfer over one pair of coils for rotating cutter with integrated thermocouple is finally set up. Figure 9(d) shows the experimental platform under the rotating state.

B. WIRELESS POWER TRANSFER TEST

The performance of the synchronous rectifier with four MOSFETs is tested first. Figure 10 shows the measured waveforms, in which the wave 2 represents the AC voltage on the receiver coil, and the wave 3 is the voltage after the synchronous rectification. The corresponding amplitudes are 22.4 V and 21.74 V. It can be obtained that there is a voltage drop of only 0.66 V, less than that using the traditional diode rectifier, whose voltage drop is 0.6 V for a single diode. Obviously, the power consumption of the synchronous rectifier would be smaller.

Then, the power transfer efficiency is tested. When the coil spacing $d$ is 4 mm, the measured load voltage and current of the receiver are 11.2 V and 140 mA, respectively, and the corresponding voltage and current of the transmitter are 12 V and 210 mA, respectively. It’s easy to calculate that the power transfer efficiency is 62.2%, which is not very high and can be improved by optimizing the selection of the appropriate operating frequency, coil spacing $d$ and coil inner diameter.
C. WIRELESS DATA TRANSFER TEST

1) DATA DEMODULATION CIRCUITS

Figure 11 gives the waveforms of the transmitter end using the synchronizing demodulation circuit to demodulate the temperature data from the receiver end, in which waveform 4 is the signal on the receiver coil with the load modulation, the waveform 2 is the temperature data signal sent by the receiver, and the waveform 1 is the demodulated data signal to the microcontroller of the transmitter for decoding. It can be seen that although the demodulated signal lags behind the sent data signal for a short time, the synchronizing demodulation circuit of the transmitter can demodulate the modulated temperature signal of the receiver effectively.

FIGURE 11. Testing the synchronizing demodulation circuit.

Figure 12 shows the waveforms of receiver end adopting the diode envelope detector to demodulate the ASK signal sent by the transmitter. The waveform 2 is the induced ASK modulation signal on the receiver coil, the waveform 4 is the signal after the diode envelope detection, and waveform 1 is the demodulated signal for decoding. These waveforms show that the envelope demodulation circuit of the receiver can demodulate the ASK modulation signal of the receiver successfully.

FIGURE 12. Testing the envelope demodulation circuit.

2) DATA TRANSFER PERFORMANCE

A test of continuously transferring a million frames of 16-bit data is employed to test the data transfer performance. The test results show that, the data from the transmitter end using the transfer rate of 3.57 kbps can be demodulated by the receiver end with the error rate of 0%. However, when the data transfer rate is up to 5 kbps, the error rate increases to about 9%. Similarly, for the sensor data transferred from the receiver end to the transmitter end, the appropriate data transfer rate of the receiver end is 5 kbps with the error rate of 0%, and if the data transfer rate increases up to 6.54 kbps, the error rate can become to be 7%. Figure 13 shows a case of the measured waveforms with failed demodulation at the data transfer rate of 6.25 kbps.

FIGURE 13. Waveforms with failed demodulation.

Based on the results above, the following conclusions can be drawn that the appropriate data transfer rate for the transmitter end and receiver end are different. Therefore, in order to achieve a fast and reliable data transfer, the transfer rate from the transmitter end to the receiver end is set to 3 kbps, and the other transfer rate is 5 kbps.

D. MILLING TEST

1) STABILITY CHECK IN MILLING ENVIRONMENT

Considering that the complexity of the milling environment may affect the stability of wireless power and data transfer, the temporary storage method is developed to verify it. The FLASH memory is used in the receiver board to temporarily store the temperature data measured by the thermocouples, which are also timely transmitted out to a host computer through the designed wireless power and data transfer module. After one milling process, the stored temperature data in FLASH memory are imported into the computer through the wired way, and then compared with the data...
transmitted through the wireless way. The experimental results show that these two data in two different ways are completely consistent at each temperature measurement time point. Therefore, application of simultaneous wireless power and data transmission over one pair of coils to transmit out the condition data and supply sufficiently stable power for the sensor-integrated systems is stable and reliable.

Besides, in the process of milling, the cutter rotates at high speed. Then, the influence of milling speed on the wireless power and data transfer is investigated by adjusting the idle speed of the milling cutter. It is found that the speed does not affect the wireless power and data transfer system, and the whole wireless system can work normally.

### 2) ACTUAL MILLING

To test the overall performance of designed wireless power and data transfer system, the integrated thermocouple is calibrated with the laser thermometer first. Then, an actual aluminum bar milling experiment is conducted, and the measured temperature curve is shown in Figure 14. There are three temperature measurement points established on the rotating cutter, including point 1 and point 2 positioned on the cutting face as shown in Figure 8, and point 3 on the cutter body. The results reveal that the temperatures of the three measurement points all increase gradually during the milling process, but the temperature rising rates of point 1 and point 2 are obviously higher than that of the point 3. This is reasonable because the point 1 and point 2 are near the cutting zone. Therefore, the cutting temperatures during the milling process can be tracked and monitored through the embedded thermocouple positioned on the cutting face, and the wireless power and data transfer system over one pair of coils is stable and practical to track and transmit out the cutting temperature data of the rotating cutter.

### V. CONCLUSION

In this work, a wireless power and data transfer system over one pair of coils for sensor-integrated rotating cutter was designed and developed. First, the scheme design, including the overall structure, system parameter and implementation scheme, is expounded. Then, the system implementation of overcoming the eddy current effect caused by the metal handle with ferrite shielding, and designing the concrete circuits of the wireless power and data transfer module is presented in detail. Finally, a milling test of aluminum bar is conducted with integrated thermocouples to measure the cutting temperatures as an illustrative example of the sensor data source, and the results demonstrate that the proposed wireless power and data transfer system can track and transmit out the condition data of rotating cutter in milling process stably. Table 2 compares this work with the representative power and data transfer systems, targeting sensor-integrated rotating devices, in the literature. This work, to the best of our knowledge, proposes for the first time a wireless power
and data transfer system over one pair of coils for rotating cutter, with low complexity of system implementation, ease integration and small volume to reduce the invasion degree of sensor system into the milling or drilling process. There may not be enough data transfer rate to transmit out the sensor data when multiple sensors are integrated into the tool holder to provide more valuable data for tool condition monitoring. Thus, in future work, the authors intend to optimize the structures and parameters of the two coils for higher rate of wireless data transfer.

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