Design of remote overload monitoring and diagnosis system for electric spindle based on three-axis MEMS device

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Abstract. The MEMS sensor is used to measure the overload signal of the electric spindle, so as to get response of overload status and send alarm signal to PLC timely, which is a kind of machine controlling tool. By this system, the collision of the electric axes can be avoided effectively. The vibration data of spindle is also can be transmitted real-timely via internet, which is supposed to be combined with data mining and machine learning for daily monitor of spindles and intelligent faults diagnose.

1. Introduction

The electro-spindle is the core part of the machine tool, accounting for about 30% of the cost of the entire machine tool. Actual production shows that most of the damage of the electro-spindle is caused by impropers operation or program errors [1]-[2].

Machine tool crashes can be found in time by the means of information technology, which seems like the airbag of cars, and it is of great value to protect the electric spindle from damage in advance[3]. In addition, if a system could transmit dynamic data of the electric spindle into backend in real time, the whole life of the electric spindle would be monitored[4].

In recent years, the fault diagnosis methods of spindles have gradually changed from traditional methods to intelligent technologies. Intelligent fault diagnosis technologies highly simulate the graphical and logical thinking ability of human beings, and integrate the knowledge and experience of human experts into diagnosis process, so to achieve reliable, real-time, deep-level and predictive fault diagnosis of large and complex equipment. The information accurately identifies and predicts the running status of diagnostic objects[5].

The data of multiple machine tools, after being clouded, will realize real-time monitoring of the spindle in the whole range. When the parameters of a system are deviating from the normal value, it is
supposed to provide a spindle operation warning to avoid the spindle working with errors and ensure process accuracy\cite{6-7}. In addition, after a long-term data accumulation, applied into big data and machine learning methods, an expert system will be formed. Based on the above status, this paper proposes a design of a remote overload monitoring and diagnosis system for electric spindle based on three-axis MEMS device.

2. Analysis of Electric Spindle Impact Process

Due to improper operation or system programming error, the electro-spindle is touched with rigid objects at a high speed or excessive cutting amount, and a collision occurs, as a consequence, the large radial reaction force will lead to permanent loss of electro-spindle. The simulated spindle collision is shown in Figure 1.

![Figure 1 Spindle collision](image_url)

![Figure 2 Impact cutting force](image_url)
For tools made of tungsten and steel, if we simulate the thrust of the CEC main shaft during the process from impact to fracture, then figure 2 can be obtained. In the initial stage, the electric spindle moves at a constant speed driven by airport motor, and it will not stop until the tool is snapped. If the tool diameter is relatively small, the reaction force will be reduced accordingly, which still can be measured by the gravity sensor.

3. Sensor design

3.1. Overall system framework

The electric spindle remote overload monitoring and diagnosis system is mainly composed of two parts: MEMS sensor and RS485. The MEMS sensor completes the acquisition of accelerated speed of the electric spindle, then sends all collected data to the host through RS485 and wireless transmission. The schematic diagram of the system structure is shown in Figure 3. This article adopts the half-duplex communication method. In order to ensure that the external host has received the sensor data successfully and returned the command promptly and effectively, it should be sent several times to avoid the communication being blocked.

![Figure 3 Monitoring and diagnosis system scheme](image)

3.2. MEMS sensor circuit design

Assume the initial speed of spindle before hit is 30m/min, and ignore the effect of the force in the initial stage. The spindle can withstand tool deformation of 0.1mm, that is, the corresponding monitoring time window is 50ms. As shown in Figure 4, in this paper, the MPU-6500 MEMS sensor is used to measure the gravity of the spindle. MPU-6500 is a 3-axis digital high-precision, small-volume sensor launched by InvenSense, which contains flowing features.

1. The accelerometer uses three 16-bit ADCs to convert the analog quantity measured by it into a digital quantity that can be output. In order to accurately track fast and slow motion, the measurement range of the sensor is user-controllable, and the accelerometer's measurement range is $\pm 2, \pm 4, \pm 8, \pm 16g$. Spindle collision, high-speed spindle instantaneously generates a large impact load, the vibration acceleration value a suddenly increases to about 9.5g, within the maximum range of the sensor, which meets the system design requirements.

2. Communication uses 400kHz I2C (Inter-Integrated Circuit) interface. The chip size is $4 \times 4 \times 0.9mm$. It adopts QFN package (leadless square package), can withstand the impact of up to 10000g, and has a programmable low-pass filter. Regarding the power supply, the MPU-6500 can
support a VDD range of 2.5V ± 5%, 3.0V ± 5%, or 3.3V ± 5%. In addition, the MPU-6500 has a VLOGIC pin to provide logic levels for the I2C output. VLOGIC voltage can take 1.8 ± 5% or VDD.

![Sensor schematic](image)

**Figure 4** Sensor schematic

The data transmission of machine tools often requires a length of several meters or tens of meters. The communication methods such as sensors or MCU's own I2C, SPI, UART (Universal Asynchronous Receiver / Transmitter) are difficult to achieve long-distance transmission. In addition, since the machine tool runs many motors, the electromagnetic environment is complex, and there is more interference, the RS485 interface is undoubtedly the best solution for low and medium speed transmission. RS485 (ANSI / EIA-485 standard) serial connection standard, realize the design of serial interface circuit. Its maximum data transmission rate is 10Mbps, and the interface is strong, that is, it has good anti-noise interference. The standard maximum transmission distance of the RS-485 interface is 4000 feet, which can actually reach 3000 meters (theoretical data, in actual operation, the limit distance is only about 1200 meters). In this article, the sensor has its own MCU, which interacts with the sensor through the MCU. On the one hand, the MCU can run in a stand-alone version and on the other hand, the external host can use RS485 to implement a certain period of time or continuous data transmission. The communication circuit design is shown in Figure 5.

![RS485 electrical connection](image)

**Figure 5** RS485 electrical connection
3.3. Design of communication protocols

In order to realize the functions of sensor configuration, data reading, data stop, etc., the communication protocol with the sensor is designed with a total of 10 instructions and parameterized. As shown in Table 1:

| Serial number | Instruction name                  | Frame header code | Command function description |
|---------------|-----------------------------------|-------------------|----------------------------|
| 1             | Configuration succeeded           | 0xD1              | Sensor correctly parses and executes PC command frames |
| 2             | Configuration failed              | 0xD2              | The sensor detected that the configuration command frames (0xA1, 0xA2, 0xA3, 0xA4, 0xA5, 0xB1) contain configuration datas that exceed the allowed range |
| 3             | Read succeeded                    | 0xE1              | Correctly perform real-time reading of sensor data |
| 4             | Read failed                       | 0xE2              | Reading sensor data in real time failed |
| 5             | Stop reading                      | 0xE3              | Stop reading sensor data execution |
| 6             | Invalid command frame feedback    | 0xF1              | The PC sends a command frame whose frame type is not within the recognizable range and the command frame header and CRC are correct. |
| 7             | Invalid CRC16 feedback            | 0xF2              | The PC sends an error when the CRC16 of the command frame is wrong and the command frame header is correct. |
| 8             | Invalid frame header              | 0xF3              | PC sends back the command frame when the frame header is wrong |
| 9             | Command frame data is too long    | 0xF4              | PC sends command frame data when it is too long (more than 20 bytes) |
| 10            | Command frame data is too short   | 0xF5              | PC sends command frame data when it is too short (less than 20 bytes) |
The following is the data frame returned by the sensor to the PC in the form of a frame structure of 12 or 65 bytes, as follows:

| Frame Header (2 Bytes) | Frame Type (1 Byte) | Frame Data (0~60 Byte) | CRC16(2 Bytes) |
|------------------------|---------------------|------------------------|----------------|
| 0xA5                   | 0x5A                | 1 Byte                 | Max bytes      |

Table 2. Frame structure form.

Among them, the data in the data area (60 bytes) is the low byte first, and the high byte is after. Pay attention when parsing. The specific sensor configuration data structure is as follows:

```c
typedef struct config_t {
    uint32_t magic_be;           // magic number, should be 0xBE
    int16_t Alarm1_Threshold[6]; //+x,-x,+y,-y,+z,-z
    int16_t Alarm2_Threshold[6]; //+x,-x,+y,-y,+z,-z
    int16_t Alarm3_Threshold[6]; //+x,-x,+y,-y,+z,-z
    int16_t Alarm4_Threshold[6]; //+x,-x,+y,-y,+z,-z
    uint8_t Alarm1_Polarity;
    uint8_t Alarm2_Polarity;
    uint8_t Alarm3_Polarity;
    uint8_t Alarm4_Polarity;
    uint16_t Alarm_HoldTime;
    uint16_t Alarm_HoldTime2; //60Bytes
} config_t;
```

After the host computer software sends a new configuration or reads the current sensor configuration command, it receives a return frame and needs to verify the correctness of the frame header and CRC16, and then parses the data area and update it to the host computer software interface in real time.

3.4. Sensor and test software design

This article uses QT for software interface design. The main implementation of the main program is the definition of various variables, the initialization of each module, the initialization of interrupts, etc. The flowchart of the program is shown in Figure 6. Starting from the main function, the system first completes the initialization settings for each module of the system, then turns on MPU6500 sensor to output interrupt every 5ms, and enters the function of the main loop.
4. Sensor physical processing and analysis of test results

The designed sensor circuit dielectric substrate uses ultra-thin ITA-9430 high-frequency copper-clad board. The packaged sensor is shown in Figure 7.

Figure 6 sensor flow chart

![Sensor Flow Chart](image)

4. Sensor physical processing and analysis of test results

The designed sensor circuit dielectric substrate uses ultra-thin ITA-9430 high-frequency copper-clad board. The packaged sensor is shown in Figure 7.

Figure 7 Physical map of the sensor

MEMS sensors can be installed on the spindle for acceleration signals’ collection, and then analyze all data to get running properties of the spindle. Figure 8 shows the comparison of the X-axis gravity induction measured over time with time. It can be seen that the safety threshold of the X axis is set to
2000. When the spindle is cutting normally, the speed runs smoothly in each speed segment, and the vibration accelerated value fluctuates among a small range. In the moment of 0.08s, the simulation of the spindle collision with the tool gave the sensor a strong impact force while the accelerated value detected by the MEMS suddenly increasing to 0.8g lasting for 25ms.

In addition, different alarm thresholds can be set according to the parameters of the spindle. In order to detect and protect the spindle away from collisions in real time, a 50ms alarm hold time is designed in this article. And two polarities are set for alarming. When the polarity is anode, once the collision occurs, the acceleration exceeds the threshold value, and the sensor outputs alarms on the rising edge, inversely, when the polarity is cathode, a falling edge alarm will be output if a collision occurs. The designed sensor is connected to FANUC's 0i-F PMC/L type. When the overload reaches the alarm threshold, the sensor circuit outputs a high level to the PLC through the output port for control.

5. Conclusion

MEMS sensors are applied in this article for data collection, which provides an electro-spindle monitoring and diagnosis system. Users can observe the operating status of the electro-spindle based on the collected real-time data, and implement corresponding controls based on parameter changes to enhance the safety of machine tool operation. It also improves the efficiency of machine operation, which holds some realistic significance. Considering the zero drift and ambient temperature of acceleration sensor, and the influence of noise, there must be some errors in the measurement results, and the measurement accuracy has a lot room to improve.

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