Design of Smart Bearing with Wireless Monitoring System

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Abstract. The paper takes the STM32F103VET6 as the core of the embedded system for wireless monitoring. This paper mainly introduces the design process of system hardware and software. The system can monitor the real-time inclination angle and temperature signals in the process of bearing operation. The monitored signals are transmitted to the host computer through the serial port. Meanwhile, they are also transmitted to the remote mobile phone through the Internet of Things.

1. Introduction

Bearings are known as the "heart" of rotating support system. They are widely used in large rotors, precision machine tools and other fields. Its operation state will directly affect the reliability and safety of the system. Smart bearing technology was born on this basis: sensors with different purposes were integrated on the traditional bearing in order to realize real-time online monitoring, fault detection and feedback control of bearing operation state. Because the sensor of the smart bearing is close to the source of signal, the precision of measurements can be greatly improved. Smart bearing technology will result in a higher success rate of early fault diagnosis. In addition, by monitoring the real-time parameter of bearing operation, the system operation state can be analyzed comprehensively. So smart bearing technology plays an important role in the development of system condition monitoring and fault diagnosis[1-4].

Robert et al. first proposed the embedded structure of installing force and temperature sensors and related electronic equipment on the outer ring of the bearing, thereby manufacturing an independent smart bearing, and proved the applicability of the sensor module through experiments[5]. Shao et al. developed a new type of multi-parameter smart bearing, including two vibration acceleration sensors, two rotation speed sensors and two temperature sensors. The embedded integration mode of bearing and sensor was adopted to extract weak fault signal. Through experiment and calculation, the bearing fault alarm can be realized[6]. Scott et al. used the inductive coupling technology to install the sensor on the bearing cage to measure the temperature and vibration signal of the bearing cage. The corresponding vibration frequencies at different speeds were measured and compared with the theoretical values. There was little difference between the experimental and the theoretical values[7]. Han et al. designed a set of bearing lubricating oil temperature monitoring system, which collected the bearing internal lubricating oil temperature through DS18B20 temperature sensor and sent real-time temperature value to the microcontroller. The microcontroller transmitted the temperature value to the display module and control module through wireless transmission. When the temperature was too high, the cooling module was turned on. The system had the advantages of stable operation, high reliability and wide applicability[8]. Wang et al. conducted a wireless monitoring scheme for the inner ring temperature of rolling bearing. The inner ring embedded the wireless temperature sensor in the bearing
lock nut. Wireless data transmission and wireless energy supply technology were used to supply power for this system. The feasibility of the scheme was verified by experiments\cite{9}. Chen et al. proposed a new method that was different from the previous method of grooving on the end face of the bearing. Compared with grooving on the outer surface, the new method had relatively small impact on the performance of the bearing. The vibration and temperature sensors were integrated on the bearing\cite{10}.

The above research on smart bearing generally focused on rolling bearing, and there is little research on monitoring the state of dynamic oil film bearing. In this paper, tilting pad bearing, a special form of dynamic oil film bearing, is designed as the research object, and a monitoring system is designed to collect the real-time inclination angle and temperature data of the bearing. In the wireless transmission, Wi-Fi module, MQTT protocol and Internet of Things are used to monitor the real-time bearing operation state from a long distance.

2. Hardware design of smart bearing monitoring system
The smart bearing monitoring system is mainly used to collect the inclination angle and temperature data during the operation of tilting pad bearing. Then this system transmits the collected real-time data to the computer and mobile phone. The system consists of four parts: inclination angle signal acquisition, temperature signal acquisition, microprocessor and wireless transmission. The block diagram is shown in Figure 1. The collected inclination angle and temperature data are transmitted to the microprocessor after signal processing circuit and A/D converter. The data can be transmitted to the upper computer through the serial port, so this system can monitor the real-time operation state of the bearing. In the meanwhile, by using MQTT protocol, Wi-Fi module transmits wirelessly the collected inclination angle and temperature data to the cloud server. After the mobile phone sends the request, the cloud server will push the data to the mobile phone, so that people can monitor remotely the real-time operation state of the bearing.

![Figure 1. Block diagram of smart bearing monitoring system](image)

2.1. Inclination angle signal acquisition module
The principle of measuring inclination signal with accelerometer is shown in Figure 2. In the horizontal position, the gravity in the positive direction of X and Y is 0 g, as shown in Figure 2 (a). Taking the Y direction as an example, when it is placed vertically along the positive Y direction, the gravity in the Y direction is 1 g, while the gravity component in the X direction remains unchanged. The gravity in the X direction is still 0 g as shown in Figure 2 (b). Conversely, if it is placed vertically along the negative Y direction, the gravity in the Y direction is -1 g, and the gravity component in the X direction is still 0 g, as shown in Figure 2 (c). The accelerometer which is only changed the gravity in the Y direction does not affect the X direction. Similarly, the situation in X direction is the same. For different acceleration values, the output signals are not the same. Based on this principle, the accelerometer can be used to measure the inclination angle.
Taking the X direction as an example, the principle of measuring the inclination angle of the accelerometer is shown in Figure 3. If the inclination angle in the X direction is $\theta$, the component of gravity in the X direction is:

$$X_g = g \sin \theta \quad (1)$$

The system used ADXL203 accelerometer from ADI Company as the inclination angle sensor with a measuring range of $\pm 1.7g$, so it can be used to measure inclination angle range $\pm 1g$. The output voltage is analog voltage, which can be processed by microprocessor after A/D conversion. The power supply voltage of ADXL203 is 3 V ~ 6 V, and the typical voltage of $V_s = 5$ V is selected. Under this voltage, the sensitivity is 1000 mV/g. Taking X direction as an example, the output voltage in X direction is $V_s/2 = 2.5$ V at 0 g, 1.5 V at -1g and 3.5 V at 1 g. Convert the output analog voltage signal $V_x$ to the corresponding value change $X_g$:

$$X_g = \frac{V_x - 2.5V}{1V/g} \quad (2)$$

According to formula (1) (2), inclination angle $\theta$ is:

$$\theta = \sin^{-1} \left( \frac{X_g}{g} \right) \div \pi \times 180 \quad (3)$$

It can be seen that the relationship between the gravity $g$ and the measured inclination angle $\theta$ is not linear, but sinusoidal. According to the characteristics of sinusoidal curve, the acceleration sensor has the best sensitivity at 0 g position, and the sensitivity becomes weaker with the increase of inclination angle[11]. Therefore, select the range near 0 g to measure the inclination angle of the bearing.

2.2. Temperature signal acquisition module

PT100 platinum resistance sensor is selected as temperature sensor. PT100 has a resistance value of 100 $\Omega$ at 0 °C, and the resistance value increases with the increase of temperature. PT100 has the advantages of high accuracy and good stability. When it is connected to the bridge circuit, the change of resistance caused by change of temperature can be converted into the tiny change of voltage. Then, this change can be amplified by the amplification circuit to achieve proper precision and measurement range. The circuit diagram is shown in Figure 4. $R_1$, $R_2$, $R_3$, and $R_4$, all the components shown in the figure, constitute the bridge circuit, and $R_4$ is PT100 temperature sensor. When $R_4$ changes, the balance of bridge is destroyed, then there will be an electric potential difference between both ends of $R_5$. This electric potential difference is very small. After $R_5$, $R_6$ and operational amplifier $J_1$ constitute an amplifying circuit, the electric potential difference is amplified, and then the temperature value is calculated based on the measured electric potential difference. AD8605 is selected for operational amplifier.

According to the principle of voltage division, the electric potential of $V_1$ is:

$$V_1 = 5V \times \frac{R_3}{R_1 + R_3} \quad (4)$$
In the formula (4), \( R_1 \) and \( R_3 \) are known quantities, and \( V_1 \) can be obtained. Similarly, the electric potential of \( V_2 \) is:

\[
V_2 = 5V \times \frac{R_{PT100}}{R_2 + R_{PT100}} \tag{5}
\]

In the formula (5), \( R_2 \) is a known quantity, \( R_{PT100} \) is an unknown quantity, and so temporarily \( V_2 \) cannot be obtained.

According to the properties of the operational amplifier: when the operational amplifier is in a linear range, the two input terminals can be regarded as equipotential. Therefore:

\[
V_3 = V_2 \tag{6}
\]

According to the properties of the amplifier circuit:

\[
\frac{V_4 - V_2}{R_6} = \frac{V_3 - V_1}{R_5} \tag{7}
\]

In the formula (7), \( R_5 \) and \( R_6 \) are known quantities, \( V_1 \) can be calculated by formula (4), \( V_4 \) can be directly obtained by microprocessor after A/D conversion, and only \( V_3 \) is unknown quantity. The resistance value of PT100 is:

\[
R_{PT100} = \frac{R_2 \times (R_5 V_4 + R_6 V_1)}{5 \times (R_5 + R_6) - (R_5 V_4 + R_6 V_1)} \tag{8}
\]

The relationship between the resistance of PT100 and the temperature \( T \) of PT100 in the range of 0 °C~850 °C is:

\[
R_{PT100} = 100 \times (1 + 3.94 \times 10^{-3} \times T - 5.802 \times 10^{-7} \times T^2) \tag{9}
\]

The temperature value can be calculated by solving the quadratic function.

![Figure 4. Temperature signal acquisition circuit diagram](image)

2.3. Microprocessor
The microprocessor adopts STM32F103VET6 of ST company as the core component of the system. It has 32-bit high-performance processor. It is easy to develop. It has the working frequency of 72MHz and the working voltage of 3.3V. There is a 12-bit ADC inside, which can directly convert the analog signals from the temperature and inclination angle sensors into digital signals and enter the microprocessor for processing. In addition, the microprocessor also controls the wireless data transmission module and executes data transmission to the upper computer through the serial port.

2.4. Wireless transmission module
Wireless transmission adopts Wi-Fi module. It has the advantages of simple use, low price, and long transmission distance. Using the ESP8266 module, the serial port is used to connect to the microprocessor. The microprocessor can be connected to the Wi-Fi network through AT commands, and the Internet of Things communication can be carried out through the MQTT protocol.

The MQTT protocol is a message transmission protocol based on TCP protocol that uses a subscription and publishing mechanism. Subscribers only receive subscribed data, and unsubscribed
data will not be received. This not only ensures the exchange of necessary data, but also avoids invalid data occupying storage and processing space. Therefore, it is widely used in the industrial Internet of Things. The MQTT protocol includes 14 messages. Among them, several messages are used commonly, such as CONNECT, PUBLISH, SUBSCRIBE, etc. The publisher transmits the data to the cloud server, and the subscriber subscribes to the publisher. Then the cloud server will push the data to the subscriber. The block diagram is shown in the Figure 5.

![Figure 5. Block diagram of MQTT protocol data transmission](image)

3. Software design of smart bearing monitoring system

3.1. Software design of lower computer

The lower computer system is completed by Keil uVision5 MKD. The flow chart of main program is shown in Figure 6. The software system of the lower computer is controlled by STM32F103. The process is divided into configuration of STM32F103 system, connected between STM32F103 and Wi-Fi by ESP8266 module, connected between STM32F103 and cloud server by MQTT protocol and data collection and transmission. First, the configuration of STM32F103 internal function library is carried out. After that, STM32F103 is connected to Wi-Fi network through ESP8266 module, and enters the next step successfully; if it is not successful, the connection between them will continue trying to reconnect. Then STM32F103 connects to the cloud server through the MQTT protocol. If the connection is successful, the program will go to the next step. However, if it fails, it will continue trying to reconnect. Finally, real-time data of inclination angle and temperature can be continuously collected and transmission through the Internet of Things technology.

The configuration of STM32F103 system mainly includes the setting of internal function library of STM32F103, such as delay function, serial port function, A/D conversion function, DMA function, timer function, etc.

The flow chart of connected between STM32F103 and Wi-Fi by ESP8266 module is shown in Figure 7, including the connection process and corresponding AT commands (AT commands in brackets), and AT commands are transmitted through the serial port. Following is the main process: first, the ESP8266 module can be reset and the STA mode can be set so that the ESP8266 module can be connected to the external mobile network. Then the automatic connection function is cancelled, and the ESP8266 module enters the external network by Wi-Fi ID name and password. If the connection is successful, the ESP8266 module enters the next step. Otherwise, it will try to reconnect with correct Wi-Fi ID name and password. Closing the multi-channel connection, the ESP8266 module will enter the cloud server by corresponding IP and port number. If the connection is successful, the ESP8266 module enters the next steps. Otherwise, it will try to connect with correct IP and port number again.

Following is the main process of microprocessor sending data to the cloud server through ESP8266: first, the parameters of the cloud server should be initialized. Three elements are required to login to the cloud server: PRODUCTKEY, DEVICENAME and DEVICESECRE. The function of the initialization is to clear the previous three elements and update the current three elements information. Then the STM32F103 connects the message to the cloud server and continuously sends the inclination angle and temperature data to the cloud server. Finally, the mobile terminal processes the messages from the cloud server and displays the inclination angle and temperature data.
3.2. Software design of upper computer

In order to prevent packet loss and bit error, the data is set to the packet mode of "frame head + data area + frame tail". The frame head, data area and frame tail are set to "AABBCCDD", the inclination angle and temperature data and "DDCCBAA". "AABBCCDD" represents for the start of the data, and "DDCCBAA" represents for the end of the data. The upper computer program is designed by LabVIEW, and the program calls VISA configuration function to set the baud rate and parity bit of the serial port. After the parameters are configured correctly, the serial port data transmission between the lower computer and the upper computer can be realized. The front panel of upper computer is shown in Figure 8. The whole smart bearing monitoring system is shown in the Figure 9. The display real-time results of mobile terminals are shown in Figure 10.
4. Conclusion
In this paper, the smart bearing with wireless monitoring system based on Internet of Things is
designed. The inclination angle and temperature sensors are embedded in the bearing tile. The real-
time inclination angle and temperature data are collected and processed by STM32F103VET6
microprocessor and transmitted by the Internet of things. The collected data has a good performance
on its accuracy due to its close position relative to the bearing. Through this system, the inclination
angle data and temperature data can be monitored remotely with the Wi-Fi module and the MQTT
protocol.

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