Design of Remote Monitoring System for Pre-Tightening Force of Anchor Bolts

Li Panfei1, *, Chen Qiankun1, Zhou Qi1, Zhang Defu1

1The 713 Research Institute of China State Shipbuilding Corporation Limited, Zhengzhou, Henan, China
* Corresponding author: lipanfei@163.com

Abstract. Given the broad monitoring range and long monitoring time of anchor bolt loosening of draught fan, and harsh site environment in offshore wind power projects, a remote temperature and pressure monitoring system was designed in this study to realize the real-time wide-range monitoring of anchor bolt loosening of draught fans. The strain pressure transducer and platinum thermistor were used at the test end to acquire the pressure and temperature data, respectively. stm32f103 was used as the master controller in the acquisition system, hierarchical networking was conducted via Modbus protocol, and the long-distance transmission was realized by a fiber optical transceiver. LabVIEW was used by the upper computer to establish the client side to implement the data acquisition, storage and real-time monitoring.

1. Introduction
In a draught fan project, the civil engineering base is connected with the upper buildings through the anchor bolts on the base, and a pre-tightening force of 60 kN-70 kN was applied to the anchor bolts during the installation of draught fan base and later-stage regular maintenance. Affected by factors like the creep deformation of internal structures in the civil engineering base, the pre-tightening force of anchor bolts is sometimes reduced and even experiences a complete failure. When the pre-tightening force of one anchor bolt is stuck in failure, the pre-tightening force of adjacent anchor bolts will be changed after the re-balancing, so the real-time monitoring is very necessary. However, the project needs wide monitoring range and long monitoring time, along with broad variation range of field temperature and very harsh site environment, imposing extremely high requirements for the sensor performance and monitoring system. There are very few monitoring facilities available in the market at present, hardly ever adapting to such harsh environment, and the ever-increasing area results in a higher cost[1-2]. Catering to this need, a remote monitoring system was designed in this study, the modules were mutually cascaded through the hierarchical networking, thus being able to realize the large-area monitoring, and the data was sent to the base station timely via the upper computer.

2. Front-End Sensor Design
Two technical routes are mainly followed in the measurement of pre-tightening force, namely, vibrating wire-type pre-tightening force measurement and strain-type pre-tightening force measurement, where the former is only applicable to qualitative measurement as its measurement accuracy fails to meet the related requirements, and the latter, which is of high precision, can meet the technical index that the error is smaller than 3% [3]. Therefore, the technical route of strain-type pre-tightening force measurement system was adopted, and the pressure sensor design is shown in Figure 1.
In order to strengthen the load-deflection resistance and temperature compensation ability of sensor, eight 00-900 strain gauges dedicated for sensor were uniformly distributed along the periphery of cylindric elastomer of this sensor, and the wiring principle of its bridge circuit is shown in Figure 2.

As the pre-tightening force of anchor bolts is greatly influenced by the temperature, the temperature and pressure were simultaneously monitored in the system design. The platinum thermistor PT100 was used to measure the temperature, to be more specific, the resistance value of PT100 was measured by constructing the bridge circuit, based on which the real-time temperature was calculated[4].

3. Hardware Design of Acquisition & Monitoring System

3.1 Networking architecture
The overall networking scheme of online monitoring system for pre-tightening force of anchor bolts is displayed in Figure 3. Multiple monitoring units were required in consideration of large monitoring area, so this monitoring system consisted of multiple monitoring units, optical fiber communication network and centralized monitoring terminal.
Each monitoring unit was composed of eight pre-tightening force sensors of anchor bolt, eight temperature sensors, one data acquisition node and one data transmission node, and the functional block diagram of each monitoring unit is seen in Figure 4.

In the acquisition system, the Modbus protocol was used to realize the cascading of acquisition modules, the data of each monitoring unit was collected into the master, and the long-distance transmission was implemented via optical fiber. At the centralized monitoring terminal, the master transceiver was connected by the upper computer software, and the real-time data of each monitoring unit could be monitored via serial port.

3.2 Circuit design principle of monitoring unit
There were eight temperature acquisition channels and eight pressure acquisition channels in each monitoring unit, where stm32f103 microcontroller was used as the master controller. The data acquired by the front-end sensor was conditioned and amplified, acquired by the 16-way AD of microcomputer, and then sent to the next node via the optical fiber network[5].

3.2.1 Power supply circuit design.
Analog power, digital power and reference power were required by the acquisition & monitoring system. The hardware circuit of power supply system is shown in Figure 5. 9V analog power was input by the external power supply, transformed into 5G digital voltage via LM2596 and then into 3.3V by AMS1117, thus supplying power to the master controller STM32 and other digital ICs.

The 9V analog power input was transformed by TPS7150 into 5V analog voltage, and then supplied to all operational amplifiers and analog devices. The 5V voltage was transformed by SPX5205 into 3.3V analog voltage as the reference power of ADC, and the 2.5V voltage output by ADR421 was used as the bias voltage of operational amplifier. XL6008 could directly elevate 5V voltage to 10V and supply to the pressure sensor.
3.2.2 Conditioning circuit.

The temperature was acquired using PT100 platinum thermistor, which needed to be connected to a bridge arm and supply power to the bridge. After filtering, the signal output by the bridge was input into MAX4194 and amplified, and entered the ADC pin. The resistance value of PT100 platinum thermistor was 100Ω at 0°C, and smaller than 100Ω at a temperature below 0°C. Under the single power supply mode, the voltage output by the bridge might be negative so that it could not be acquired. There are two solutions: The resistance value of adjacent bridge arm can be properly reduced until it is smaller than that of sensor; or, a bias voltage may be added into the MAX4194 amplifier, and the value of bias voltage is namely the measurable minimum negative voltage[6]. In this design, both solutions were used, the value of R27 was regulated to 82Ω, and the bias voltage REF0 of MAX4194 was 1.25V, as shown in Figure 6.

![Fig.6. Temperature Acquisition Circuit](image)

Where the amplification factor of operational amplifier MAX4194 is as below:

\[ Gain = 1 + \frac{2Rx}{Rg} \]  

(1)

Where Rx is a fixed value 25KΩ, and Rg is R26 in the external resistor, being 1.8kΩ. According to Equation (1), the amplification factor of temperature was calculated as 28.8.

The output of pressure sensor was a millivolt-level bridge circuit signal, which could be directly filtered and amplified. The amplification factor should ensure that the voltage input into ADC was not greater than the reference voltage 5V. In this design, as shown in Figure 7, Rg was namely R9, being 330Ω, and the amplification factor was calculated as 152.5 according to Equation (1).

![Fig.7. Pressure Acquisition Circuit](image)

3.2.3 Communication circuit.

Industrial serial port-to-fiber optical transceiver was used in this design, with the interface design as shown in Figure 8, transmission rate of below 10 Mbps and single-mode transmission distance of 20 km.
During the operating process, the controller continuously acquired the values of temperature and pressure sensors, conducted the real-time calculation, and updated the calculation result into the Modbus register. If a receiving interrupt occurred to the serial port, the master sent data via optical fiber, and slave implemented the processing accordingly according to Modbus protocol[7].

### 3.3 Algorithm design

The 16-channel (8 temperature acquisition channels and 8 pressure acquisition channels) 12-bit ADC in Stm32rbt6 was used in this system. Both sampling rate and precision could meet the design requirements. The DMA configuration was adopted, thus improving the operating efficiency.

#### 3.3.1 Temperature algorithm.

The temperature value was calculated through the resistance value of PT100 platinum thermistor, so it was only necessary to calculate the resistance value. According to the design method of temperature bridge circuit as shown in Figure 6, the relation between PT100 resistance and AD_Value received by AD could be obtained as follows:

\[
\frac{R_{30}}{R_{30}+R_{27}} \cdot \frac{R_{31}}{R_{31}+R_{pt}} \cdot V_{REFX} \cdot Gain = AD\_Value \cdot \frac{3.3}{4096} - V_{REF0}
\]  

Where Rpt is the real-time resistance of platinum thermistor PT100, VREFX is the supply voltage of bridge circuit, VREF0 is the bias voltage of operational amplifier, AD_Value is the sampling value of ADC, and Gain is the amplification factor of temperature signal.

According to AD value of sampled data, the resistance value of PT100 could be solved through Equation (2). Based on the equation given in the standard IEC751, the following holds within the temperature range of -78°C-0°C:

\[
R_t = 100 \left[ 1 + 3.90802 \times 10^{-3} \cdot t - 0.5802 \times 10^{-6} \cdot t^2 - 4.27350 \times 10^{-12} \cdot t^3 \right]
\]  

Within the temperature range of 0°C-600°C:

\[
R_t = 100 \left( 1 + 3.90802 \times 10^{-3} \cdot t - 0.5802 \times 10^{-6} \cdot t^2 \right)
\]  

![Fig.8. Optical Fiber Interface Circuit](image-url)
Where \( t \) is the temperature and \( R_t \) is the resistance value \( R_{pt} \) solved in Equation (2).

The related program was compiled according to Equations (2), (3) and (4). The real-time temperature value \( t \) could be calculated according to the AD value. As the stm32 microprocessor can directly implement the multiplication and division operations of floating-point number, Newton iteration method was used in this algorithm, so that the result could be precise to 0.1% after the three iterations[8].

3.3.2 Pressure algorithm.
The voltage value output by the pressure sensor was linearly correlated with the pressure value. The pressure sensor was measured, its sensitivity was acquired as \( S_n \) (mV/V), and then the relation between pressure value \( P \) and AD_Value received by AD is as below:

\[
\frac{P \cdot S_n}{P_{max} \cdot 1000} \cdot V_{supply} \cdot Gain = AD_{value} \cdot 3.3 \div 4096 - V_{offset}
\]

(5)

Where \( P \) is the measured pressure value, \( P_{max} \) is the range of sensor, \( V_{supply} \) is the excitation voltage of sensor, \( AD_{value} \) is the sampling value of ADC, \( V_{offset} \) is the bias voltage of operational amplifier, and \( Gain \) is the amplification factor of pressure signal.

According to Equation (5), the real-time pressure value could be calculated through the sampling value of ADC.

3.4 Communication protocol
The Modbus protocol was used in the monitoring system to realize the communication and mutual data transmission among the controllers, so as to achieve the centralized and distributed data control. Each monitoring unit at the data acquisition terminal served as a Modbus slave while the centralized acquisition terminal as the master, which read and wrote the slave register by the inquiry mode. The transmission mode of Modbus RTU was used, and its data frame format is seen in the following table.

| Start bit | Device address | Function code | Data | CRC check | End mark |
|-----------|----------------|---------------|------|-----------|----------|
| 3.5 characters | 8bit         | 8bit         | N 8bit | 16bit     | 3.5 characters |

In Table 1, there was 3.5-character waiting time when each segment of data was started or ended. The function codes in this design were 03 and 06, where 03 was used by the master to read data from slave, and 06 was used to control the communication mode of slave.

4. Software Design of Acquisition & Monitoring System
The software design of upper computer in this acquisition system was done via LabVIEW. The serial port data of master was read using the VISA serial port configuration module. When the data sent from the serial port was detected, the upper computer system read the data in the buffer zone of serial port, the header file was then judged, and if it was correct, decoding, checking and interpretation of Modbus data received by the serial port were conducted, the data was transformed into decimal data, followed by cyclic display and storage on the front panel of monitoring system[9-10]. The temperature and pressure values were judged by the LabVIEW acquisition system. If the present values exceeded the preset range, the corresponding alarm light would flicker. The software workflow is shown in Figure 9.
Read data from COM port

Initialization

Are the file headers corresponding?

Y

CRC check done?

Y

N

Delete data in this group

N

Extract data at each measuring point and transform it into decimal data for calculation

Output, display and save

Fig. 9. Workflow Chart of Upper Computer

5. Conclusion
An acquisition system applicable to long-term, long-distance and wide-range monitoring was designed in this study, so was a front-end acquisition circuit, which aimed to supply voltage to sensors, and this system was also configured with filtering and conditioning modules. Hierarchical network was implemented via Modbus communication protocol, thus realizing the cascading of different modules. Each acquisition & monitoring unit was connected to the master using optical fiber communication, which enhanced the system flexibility and lowered the application cost. By an experimental verification, this system is characterized by high reliability, low cost, timeliness, wide range of application, and also good universality, as it is capable of acquiring signals like voltage, current, temperature and humidity, pressure, strain and acceleration just by changing the connection of front-end acquisition circuit.

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