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# A Port Crane Strain Measurement System Using Integrated Foil Gauge

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**Abstract.** A strain measurement system is designed to realize real-time monitoring of port crane strain and estimate the fatigue life of port crane. On the hardware side,the differential input of weak signal of ST350 strain sensor is realized by high-precision amplifier AD620, and the interference is filtered by two-stage filter. On the software side, the strain measurement system is developed based on C#.The system can acquire data and store it to the SQL Server database. 8-level load spectrum of port crane is compiled based on MATLAB to estimate the fatigue life of port crane.The interface program is written by VB.net to transmit the acquired data to the PI System. The PI System canstore the data andpublish the conditionof port crane to the web page.The test results show that the performance of strain measurement system real-timeis good, the accuracyof the integrated foil gauge is good, the fatigue life of port crane can be effectively estimated.

**Keywords:**strain measurement; dataacquisition; data transmission; PI System;data processing; Fatigue life.

## 1. Introduction

Port crane is an important handing equipment for port production. With the rapid development of industrialization, crane gradually shows the characteristics of large-scale equipment, high production efficiency, complex technology and strong operation continuity. The operating state of crane affects the production efficiency and economic benefits of the port. So, it is very necessary to monitor the operating state of port crane. Traditional state of crane monitor is accomplished by manual, timing and fixed-point method. The monitor method is simple and the condition evaluation depends on human’s experience. Remote monitoring technology is widely used in industrial production site, which can monitor the operating state of equipment in real time. In recent years, with the development of artificial intelligence, remote monitoring of port cranes can be easily realized, which greatly improves the efficiency of troubleshooting equipment and ensures the normal operation of equipment[1], [2].

In mechanical engineering, Strain measurement is one of the important means to analyze the stress state of parts and structures, to evaluate the mechanical properties of materials, to measure the in-plane high-accuracy deformation, and to study the mechanism of some physical phenomena.Strain gauge is one of the important parts of strain measurement. The traditional strain sensor is mostly patched strain gauge. This way requires field patching to form Wheatstone Bridge Road, which is troublesome to operate and vulnerable to weather[3], [4].The ST350 strain sensor introduced by American Bridge Diagnostics Corporation is an integrated foil gauge. The ST350 has three kinds of bridge modes: single arm, half bridge and full bridge.The strain gauge can be fixed to the DUT within a few minutes without being affected by the weather. Its sensitivity is 3.5 times of general foil strain gauge. It greatly improves the efficiency and accuracy of strain measurement.

## 2. System hardware

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The main hardware of the system includes strain sensor, signal conditioning circuit, data acquisition card, computer. The system schematic diagram is shown in Figure 1.

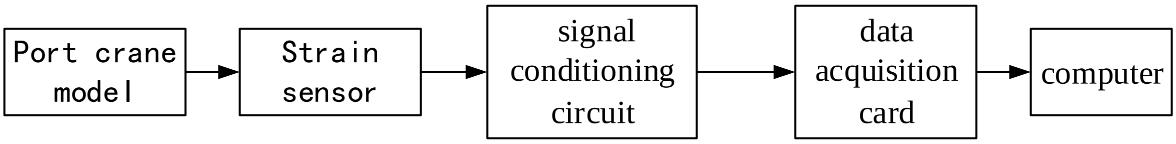


Fig.1: system principle schematic.

## 2.1. Strain sensor

The internal components of the ST350 consist of a custom-manufactured 350-Ohm Wheatstone bridge foil transducer-class strain gage mounted inside a flexible proving ring. The four active arms are arranged inside the ring in such a manner that the total output provides approximately 3.5 times the output compared to a typical ¼-bridge foil gage under the same induced strain level.

The ST350 produces a voltage potential across opposing Wheatstone Bridge corners (Figure 2) which varies with tension and compression. The sensitive (longitudinal) axis is parallel to the face of the serial plate on the top of the sensor housing (direction of the cable exit).

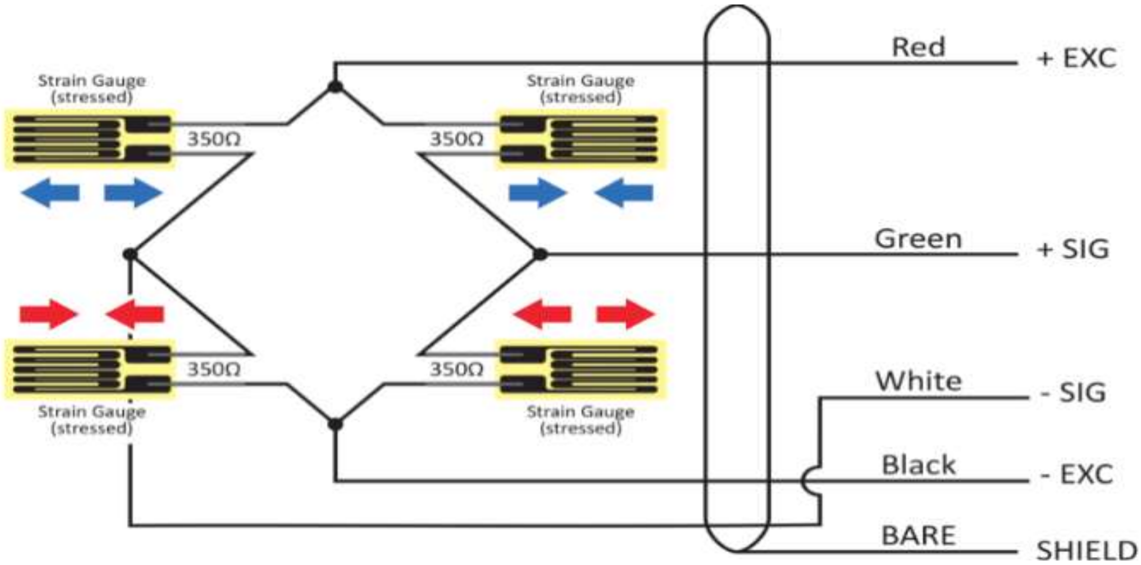


Fig.2: ST350 Schematic.

Each ST350 is supplied with a N.I.S.T. traceable calibration factor. Since this sensor is a ratiometric sensor and can be supplied a range of excitation voltage. The supplied calibration factor is normalized for excitation voltage. To calculate the proper calibration factor for the data acquisition system, the excitation voltage that is used must be multiplied by the General Gage Factor (GGF). The following is an example of the supplied calibration factor:

GGF = ### με/mVout/Vexc

Where: GGF = General Gage Factor; ### = Numeric Calibration Factor; με = microstrain (strain x 10-6); mVout = Output Voltage in Millivolts DC; Vexc = Excitation Voltage supplied to sensor in Volts DC.

The ST350 strain gauges used in this system are full bridge strain sensors B6715, B6716, B6717 and B6718. As shown in figure 3.

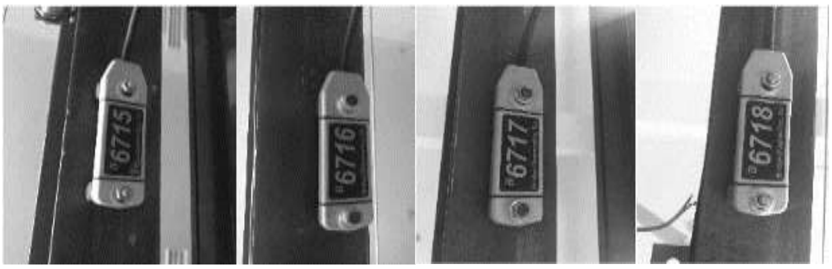


Fig.3:strain gauges.

### 2.2. Signalconditioning circuit

The signal conditioning circuit is composed of instrument amplifier AD620 and filter circuit.The functional structure of AD620 amplifier is shown in Fig 4.

In order to filter the interference signal and the high-frequency noise generated by the integrated chip, after amplifying the sensor signal, the active low-pass filter is used to filter the high-frequency interference signal. In this design, the fifth-order filter circuit is constructed by two second-order filters and one first-order filter, which can effectively eliminate interference. It can effectively improve the signal-to-noise ratio[5]. The circuit is shown in Fig 5.

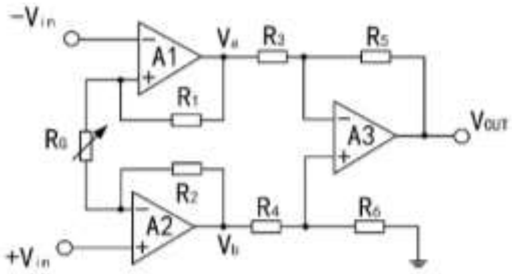


Fig.4:AD620 function construction diagram.

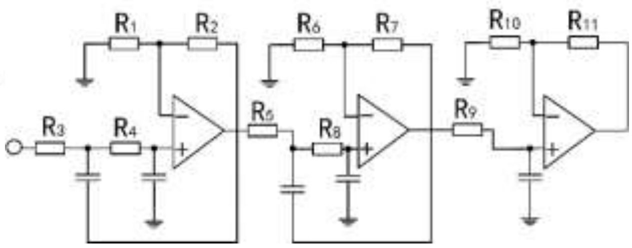


Fig.5: Filter circuit.

### 2.3. Data acquisition card

In this test system, the USB6000 data acquisition card developed by NI company is selected. The data acquisition card has 12-bit resolution and provides USB interface, 8 single-ended analog input channels, 10 KS/s single-channel sampling rate, 4 digital input/output channels and 2 32-bit counters.

## 3. System software

On the software side, the strain measurement system is programmed by C# and the data acquired by the system is saved to the database. To get the fatigue of the port crane, MATLAB is used to analyse the strain data. VB.net is used to compile the interface program to transfer the collected data to PI server. software flow chart is shown in Figure 6.

The strain measurement system includes strain data acquisition and historical data query. Before data acquisition, various settings about data acquisition are carried out, for example, sampling frequency, sensitivity, corrected value and so on. Then, the collected data are saved to the SQL Server database in real time; The historical data query part reads the data from the database, and display the data on the show interface. The strain measurement system programmed based on the C# can monitor the state of each sensor and the information acquired by the sensor.

After collecting data, MATLAB is used to program the load spectrum of port crane. The computer that acquires and analyses strain data and the server computer are connected to the same LAN by router to realize data transmission. VB.net is used to compile interface program to realize the transmission of strain data to the PI server. The data transmission interface is shown in figure 7.

At last, transmitting data to PI system. In PI system, a point isbuild by point builder to store the original strain data and the data processed by MATLAB. Then the interface is configured so that two computers can transmit data.PI system has powerful real-time data acquisition function. It can acquire raw data from different data sources in real time. Through user configurable reports, analysis tools and Web software tools provided by the system, it can display the current and historical running status on desktop computers, portable computers or mobile PDAs that are distributed all over enterprises or management departments in real time. PI system is shown in figure 8.

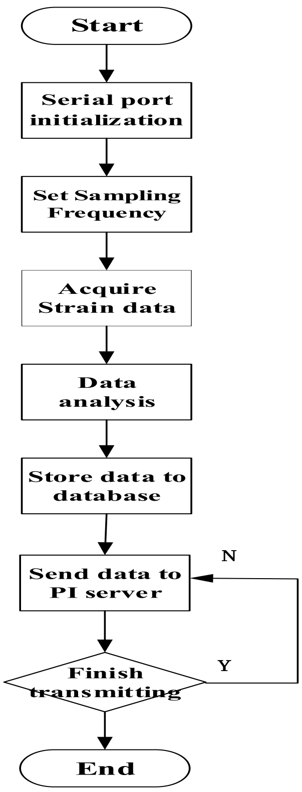

Fig.6: Software flow chart

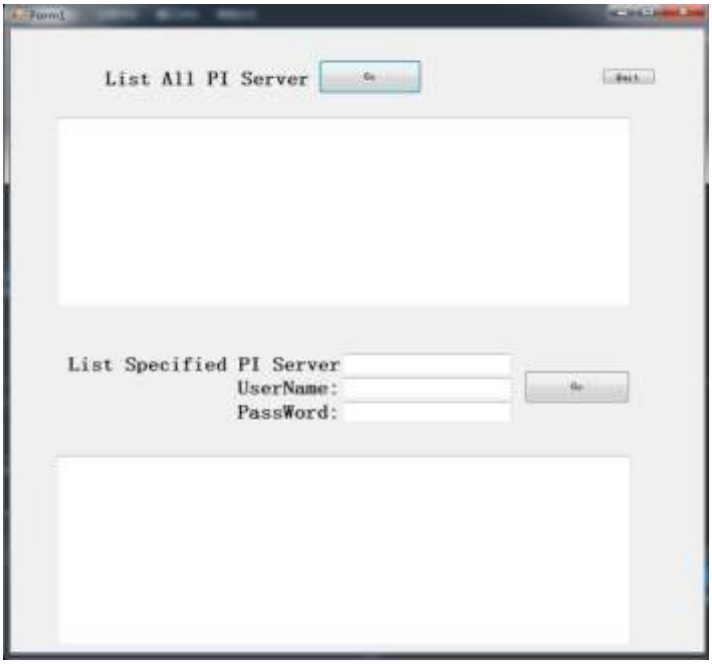

Fig.7: Data transmission interface.

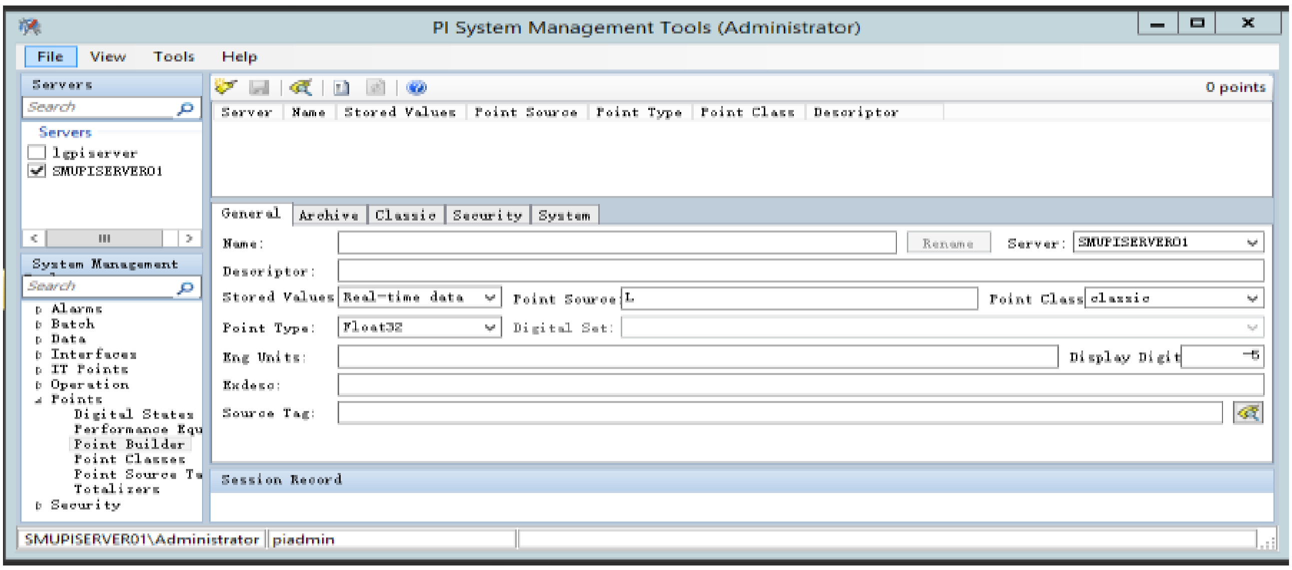

Fig.8: PI system.

# 4. Experimental Test

## 4.1. Data acquisition

Four test points are arranged in the design. The location of the measuring point is shown in Figure 9.

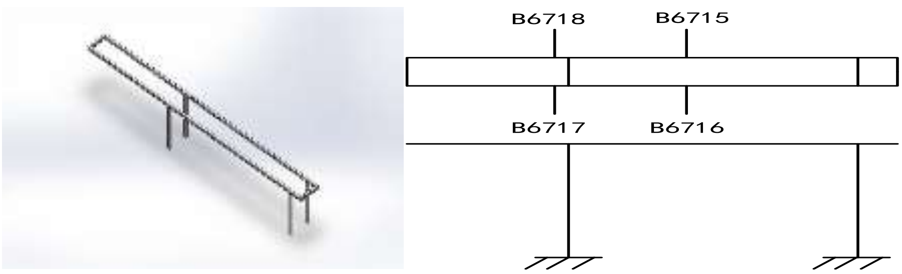

Fig.9: The location of the measuring point.

The strain value in this design is calculated according to equation (1)

$$\varepsilon = G \times (X \times 1000 \div W \div Y + F) \tag{1}$$

Where:

X = Output Voltage of DAQCard, Y = Excitation Voltage, G = General Gage Factor, W = Amplification Factor of Signal Conditioning Circuit, F = Field Strain Gauge CorrectedValue (mV/V).

In this experiment, the sampling frequency is 50Hz, the excitation voltage Y = 5V, the strain gauge corrected G is shown in Table 1, the amplification factor F = 400, and the corrected value of strain gauge in the field is shown in Table 1.

Table 1: General Gage Factor and Strain CorrectedValue.

| NO. | G | F |
|---|---|---|
| B6715 | 498.9 | 0.553 |
| B6716 | 507.7 | 1.065 |
| B6717 | 506.1 | 1.015 |
| B6718 | 508.1 | 0.265 |

The strain real-time acquisition graph is shown in Fig. 10, and the strain history query graph is shown in Fig. 11.

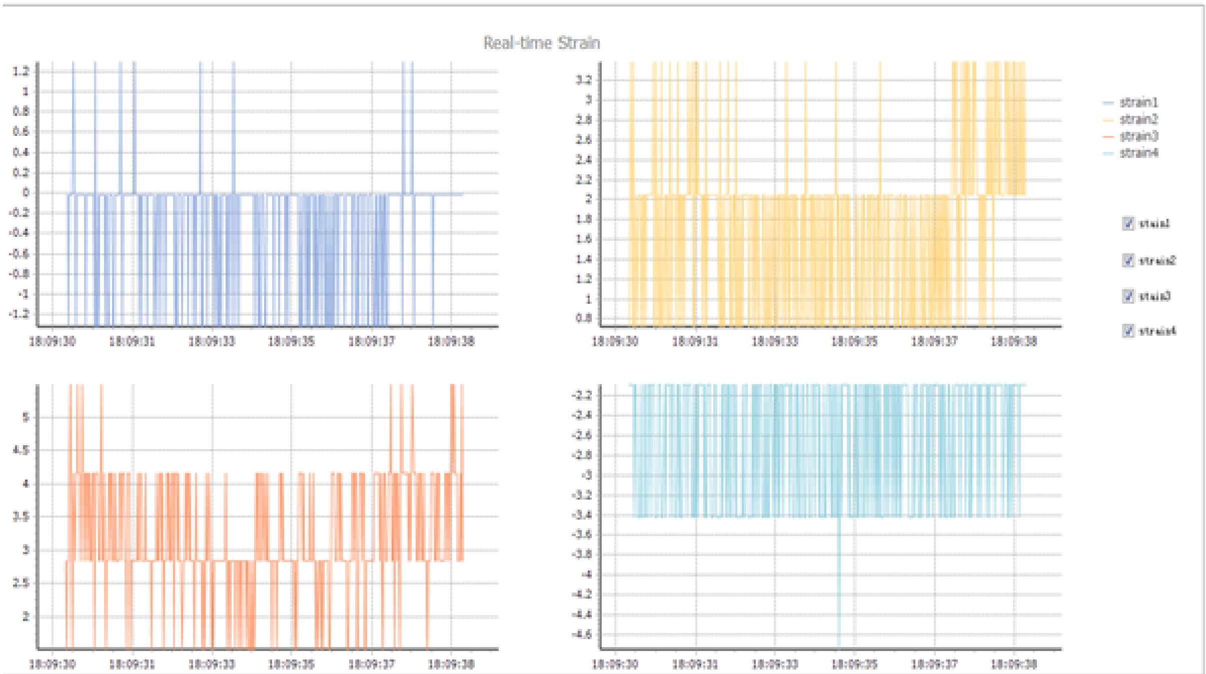


Fig.10: The strain real-time acquisition graph.

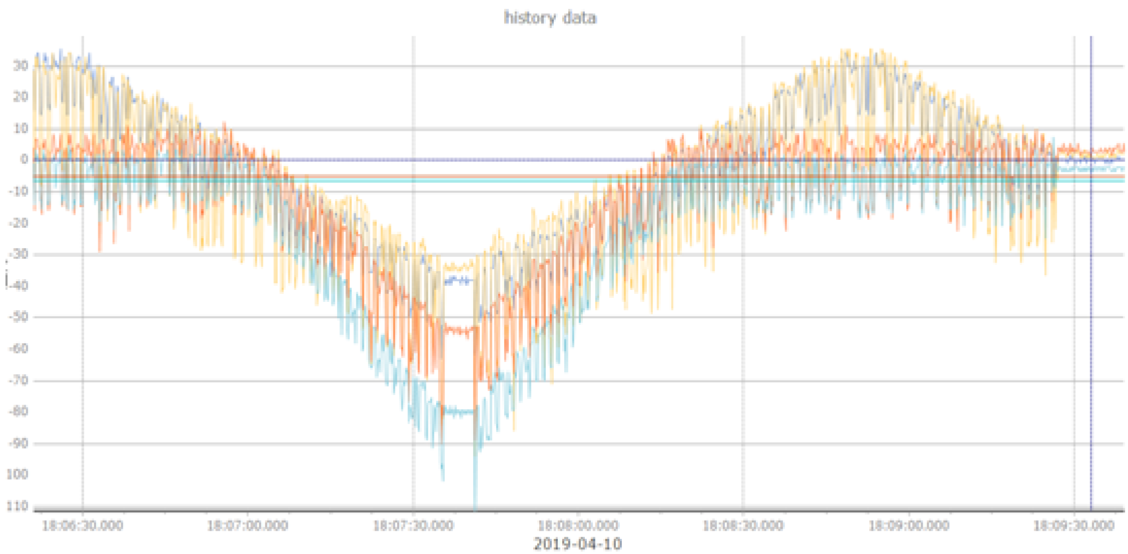


Fig.11: The strain history query graph.

## 4.2. Fatigue Life

The acquired data are preprocessed, and the preprocessed data are counted by rain flow statistical method. The load spectrum is compiled after Goodman zero-mean processing. The compiled load spectrum is extended by the parameter extrapolation method to achieve the frequency amplitude. Finally, combining the crane S-N curve, estimate the life of the port crane model [6].

### 4.2.1. Load Spectrum

The collected data are pre-processed to filter out the data which have little effect on fatigue life to improve the whole calculation speed. It has been pointed out by fatigue tests that the stress amplitude does not exceed 13% of the maximum cyclic stress can be removed and the fatigue life will not be significantly affected. Based on the literature reviewed, the invalid amplitude of cyclic stress less than 10% of the maximum stress amplitude is removed[7].

Extracting peak and valley values in load cycle is the requirement of rainflow counting statistics, and is also prepared to eliminate invalid amplitudes.The criteria for judging whether a point is a peak-valley point are as follows: set the array to be processed to E2(n2), and the resulting array is F2(n2), I and j are cyclic variables of the two arrays respectively. When (E2(i)-E2 (i-1))*(E2(i)-E2 (i+1))> 0, the point is a peak or valley point. After extracting the peak and valley values, the rainflow counting statistics are carried out on the data[8].

In the fatigue life estimation of cranes, the structural stress after rain flow counting should be transformed into the stress spectrum under symmetrical cycle. In this paper, Goodman equal-life method is use to obtain zero mean stress spectrum[9].

In order to facilitate the compilation of load spectrum and the calculation of fatigue life, the load spectrum of port cranes are compiled by 8-level load spectrum.In this paper, the load spectrum of each measuring point are plotted by MATLAB. using the strain gauge measuring point B6715 as an example to illustrate. The frequency of fatigue stress obtained when the weight of the trolley on the crane is 20 kg is shown in Table 2. Histogram of B6715 point amplitude frequency is shown in fig12

Table 2: Frequency Table of Equivalent Fatigue Stress at B6715 Point.

| Amplitude（Mpa） | Frequency | Cumulative frequency |
|---|---|---|
| 1.031 | 15647 | 15652 |
| 2.838 | 1 | 5 |
| 4.646 | 1 | 4 |
| 6.453 | 0 | 3 |
| 8.261 | 1 | 3 |
| 10.069 | 0 | 2 |
| 11.876 | 0 | 2 |
| 13.784 | 2 | 2 |

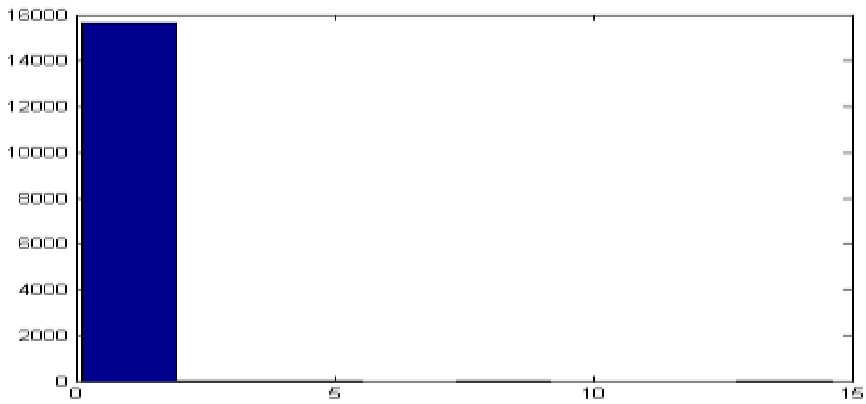


Fig.12: Histogram of B6715 Point Amplitude Frequency.

Generally speaking, the collected load-time history is a small part of the whole life cycle, and it is difficult to ensure that this process contains the maximum load in the whole life cycle.The results show that the cumulative frequency of load value should be extended to$10^6$cycles.In this paper, to obtain more real field loads that may occur in the whole life of the structure, a widely used method of parameter extrapolation is used to extend the cumulative frequency to $10^6$ cycles[10].

The formula for calculating the extended frequency is as follows:

$$N_i' = k * N_i \tag{2}$$

Where:

$N_i'$-Frequency after extension under a cyclic stress; k-extension factor, k=$10^6$/N;

$N_i$-Cumulative frequency under a cyclic stress; N-Total cumulative frequency before the amplitude extension, $N = \sum_{i=1}^{8} N_i$. The extended load spectrum at point B6715 is shown in Table 3.

Table 3: The extended load spectrum at point B6715.

| Amplitude（Mpa） | Frequency | Cumulative frequency |
|---|---|---|
| 1.031 | 999680 | 1000000 |
| 2.838 | 64 | 320 |
| 4.646 | 64 | 256 |
| 6.453 | 0 | 192 |
| 8.261 | 64 | 192 |
| 10.069 | 0 | 128 |
| 11.876 | 0 | 128 |
| 13.784 | 128 | 128 |

### 4.2.2. Fatigue Life Estimation

This paper refers to the design specifications of cranes to determine the S-N curve of crane components[11]. In this paper, the material for life estimation of port crane is Q235 steel, tensile strength $\sigma_b$=420Mpa, fatigue limit $\sigma_{-1}$=192Mpa.The S-N curve equation of port crane obtained by modifying the S-N curve of the original material is:

$$\mathrm{lgN} = -6.05\mathrm{lg}\sigma + 16.136, \sigma \geq 42.3 \tag{3}$$

$$\mathrm{lgN} = -2.31\mathrm{lg}\sigma + 10.057, \sigma \leq 42.3 \tag{4}$$

According to Miner's linear cumulative damage theory [12], the life of port crane is estimated. The modified Miner's theory is expressed as follows:

$$\mathrm{D} = \sum_{i=1}^{k} \frac{n_i}{N_i} = a \tag{5}$$

Where: a=0.7.

This paper takes B6715 as an example to illustrate the fatigue life estimation.The stress spectrum data of B6715 point is shown in table 4.

Table 4: The stress spectrum data of B6715 point.

| Amplitude（Mpa） | Frequency $n$ | Fatigue cycle Life$N$ | Damage degree $D_i$ |
|---|---|---|---|
| 1.031 | 999680 | 1.06E+10 | 9.41E-05 |
| 2.838 | 64 | 1.02E+09 | 6.25E-08 |
| 4.646 | 64 | 3.28E+08 | 1.95E-07 |
| 6.453 | 0 | 1.54E+08 | 0 |
| 8.261 | 64 | 8.68E+07 | 7.37E-07 |
| 10.069 | 0 | 5.50E+07 | 0 |
| 11.876 | 0 | 3.75E+07 | 0 |
| 13.784 | 128 | 2.66E+07 | 4.81E-06 |

The total damage degree of B6715 in one year is as follows:

$$\mathbf{D} = \sum_{i=1}^{i=n} \boldsymbol{D_i} = \mathbf{9.99 \times 10^{-5}}$$

Therefore, at the B6715 point, life of the equipment can be estimated as follows:

**N=0.7/$\mathbf{9.99 \times 10^{-5}}$**=7007.7(years)

The life estimating process of other measuring points is the same as that of B6715, so it is not explained here.

## 5. Conclusion

The strain measurement system of port machinery developed by C#, VB. Net, Matlab and PI servers can realize data acquisition, storage, processing and analysis, and real-time monitoring of port crane state.

The measurement part of the system is realized by software, which has the characteristics of simple operation, strong expansibility, high performance and strong maintainability. The strain data acquired by integrated strain gauge ST350 sensor are accurate, flexible and convenient.Theacquired data is sent to PI server and published to the web page. The state of the port machine can also be viewed through other terminals.

Because the trolly load of the laboratory model is very small, the life estimated by B6715 point is 7000.7 years, which is quite different from the actual life of the port crane.

## 6. Acknowledges

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