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Intelligent monitoring and diagnosis for modern mechanical equipment based on the integration of embedded technology and FBGS technology

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ABSTRACT

The embedded technology as a technological fundament plays an important role in the intelligent monitoring and diagnosis for modern mechanical equipment (MME). The fiber Bragg grating sensor (FBGS) technology has been rapidly applied to most of the industrial and mechanical engineering fields in recent years. This paper focuses on the new principle and new method of intelligent monitoring and diagnosis system for MME based on the integration of embedded technology and FBGS technology. According to the principle of embedded technology, the embedded network and fieldbus gateway for the integration of monitoring and diagnosis system are investigated, and the embedded high-speed demodulation is studied. Based on FBGS, the new embedded sensor for online state monitoring of MME is introduced. Moreover, the embedded sensing signal processing and data transmission, which can meet the requirements of multi-parameter measurement, synchronous sampling and long-term intelligent monitoring for MME, are proposed. In addition, by integrating the FBGS technology and embedded technology, the embedded integration system of intelligent monitoring and diagnosis for MME is presented.

1. Introduction

How to improve the intelligence, reliability, precision, compatibility, interoperability and manageability of MME, devices and systems, is always an important issue to which modern mechanical production has paid great attentions. The key issues, which are hindering the improvement of the performance and accuracy of MME and devices, as well as the development of intelligent mechanical monitoring and diagnosis technology, include the high-speed signal acquisition and processing technology, the intelligentization and popularization of devices, the communication, networking and interconnect diagnosis technology of equipment.

The embedded system is a technology-intensive, capital-intensive, highly dispersed and constantly innovative expertise integrated system which holds the following advantages: (1) it is application oriented, that is, to meet the specific requirements of each application, it can be designed with the simplest hardware and software structures; (2) it takes computer technology as its foundation; (3) its software and hardware can be flexibly cut down; and (4) it can perfectly meet the requirements of function, reliability, cost, volume and power consumption of different application systems. According to the comments of the International Institute of Electrical and Electronics Engineers (IEEE), the embedded system is defined as *devices used to control, monitor or assist the operation of equipment, machinery or plants* [1]. Since the intelligent monitoring and diagnosis system for MME is based on networks and intelligent equipment, and the utilization of embedded system can enable much more equipment to

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be intelligent and have the capacity of network communication, the embedded technology will play an extremely important role in and greatly accelerate the development of modern mechanical intelligent monitoring and diagnosis [2,3].

Due to the reason that the structures of the MME are complicated and the working conditions are high temperature, high pressure and high rotation speed, its status is characterized by diversity, coupling, and nonlinear. Unfortunately, the traditional monitoring methods can not meet the requirements of multi-parameter, huge capacity, distributed, and real-time online detection and monitoring. FBGS is characterized by miniature dimension, explosion-proof, electrical isolation, immunity to electromagnetism interferences, high precision, high reliability, and good environment adaptability. Moreover, as several measurement gratings can be deployed on one single fiber (which can be seemed as a distributed sensor) to measure different parameters, the real-time status measurement for multi-parameter and multi-field can be implemented [9]. Therefore, it has very broad application potential in civil, industrial, and defense areas. In recently years, the FBGS has been applied to modern mechanical engineering for intelligent monitoring, and the FBGS technology shows strong vitality and prosperous application foreground for the intelligent monitoring and diagnosis of MME [4,5]. Therefore, the FBGS technology together with the embedded technology are the promising solution to intelligent monitoring and diagnosis for MME, especially for the heavy duty mechanical equipment. But now, the relatively laggard fiber Bragg grating (FBG) demodulation technology has seriously restricted the performance and application efficiency of FBGS. As a result, the demodulation technology of FBGS has become the main obstacle to the wide application of FBGSs, and thus has been considered as an important research topic and a key issue needed to be addressed urgently. Furthermore, to implement the online intelligent monitoring and diagnosis system with distributed multi-parameters based on the embedded and FBGS technologies, the embedded integration architecture and hardware-software co-design method will become the research trend of intelligent monitoring and diagnosis for MME.

2. The integration of monitoring and diagnosis based on embedded technology

The intelligent monitoring and diagnosis system for MME is such a technical system that seamlessly integrates the manufacturing technology, intelligent technology and communication network technology. The monitoring and diagnosis process of the system is the process of information acquisition, transmission, processing and utilization. Since an integrated intelligent remote monitoring and diagnosis system consists of a variety of network equipment distributed at different locations which are connected by different kinds of networks (e.g. LAN, WAN, fieldbus, etc.), the network interconnection technologies must be employed to realize the intercommunication between the distributed equipment. Furthermore, the wide-range sharing of resource and information, and the remote monitoring and diagnosis of equipment must be implemented. Therefore, the modern intelligent monitoring and diagnosis system should be built based on the communication network. The development of embedded technology is possible to boost the rapid development of network interconnection and communication technologies, which would achieve the goal of interconnection between heterogeneous networks and remote equipment and realize the remote intelligent monitoring and diagnosis.

2.1. The integration of monitoring, diagnosis and management decision-making based on embedded technology

The embedded technology based internet consists of several subnets and the network resource of each subnet can be shared by all users of the whole network. Meanwhile, the equipment, resources and services connected to the internet can act as a whole by shielding the heterogeneity of each subnet in its protocol, service and network management.

The interconnected logical structure of the monitoring and diagnosis system based on embedded technology is shown in Fig. 1.

As shown in Fig. 1, the embedded based interconnected layer plays an important role in the consistent connection of the monitoring and decision-making management network. On the one hand, it transforms information derived from the monitoring network into an appropriate format that can be understood by the management network. On the other hand, it transforms the monitoring, diagnosis and configuration information derived from the management network into the format that can be understood by the equipment. Therefore, the interconnected layer is characterized by high efficiency, strong fault-tolerance capability, security, and reliability.

There are different technical methods to form the integrated monitoring, diagnosis and management systems with different network structures. Fig. 2a shows a kind of network architecture of the integrated monitoring, diagnosis and management system. The system integrates both the monitoring and diagnosis network and the management network which are connected with the fieldbus via routers. Fig. 2b shows another kind of system architecture, from which we can see that the monitoring and diagnosis network and the management network are independent and connected by routers. The two kinds of network architectures mentioned above can be flexibly adopted according to the practical requirements.

2.2. The transparent access of underlying devices

The underlying devices of monitoring and diagnosis system are often connected to the fieldbus and are always heterogeneous. Based on the embedded technology, each underlying device and sensor is regarded as a network node which is switched into the heterogeneous fieldbus sensing network transparently. Different subnets interconnect with each other through the fieldbus gateway and the problems of data sharing and remote centralized

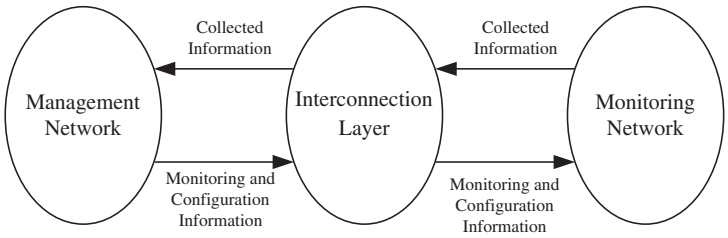
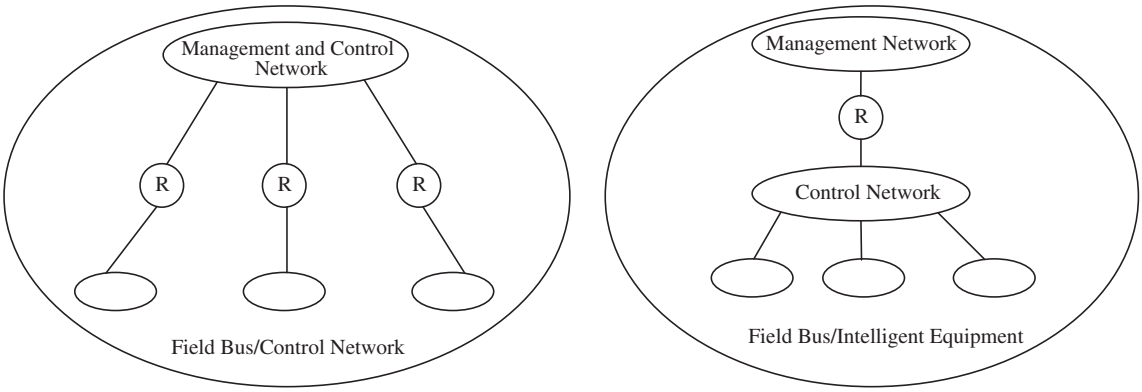


Fig. 1. The interconnected logical structure of the embedded technology based monitoring and diagnosis system.



(a) Group networking of Management and control (b) Separate networking of Management and control

Fig. 2. The network architectures of the integrated monitoring, diagnosis and management system.

monitoring and diagnosis are solved by transforming the industrial-onsite-based-network information into the information that supports TCP/IP protocol.

2.2.1. Embedded fieldbus gateway

The embedded fieldbus gateway is fit for fieldbus such as CAN, DeviceNet, and fieldbus. Bus gateway provides an embedded based network monitoring platform which is an exterior diagnosis equipment compatible with K-line interface, USB interface as well as wireless interface. As shown in Fig. 3, the gateway mainly consists of field subnet interface, WAN interface, and CAN/DeviceNet—TCP/IP data processing card. Among them, the WAN interface is used to send and receive TCP/IP data, the CAN/DeviceNet—TCP/IP data processing card is employed to transform CAN/DeviceNet data into TCP/IP data or vise verse, the K-line interface is used to connect special diagnosis equipment, the USB interface is adopted to connect universal portable computers, and the network and fault diagnosis protocol transformation and processing card is employed to transform the CAN/LIN data into TCP/IP data or implement the process of compatible OBDII/KWP2000 fault diagnosis data.

2.2.2. Information integration technology

During the design process of gateway, in order to share the monitoring and diagnosis information among different fieldbuses, the matching and connecting issues between different bus subnets should be considered. In order to realize the information integration of different fieldbus subnets, each kind of subnet must have an independent gateway with a subagent (SA) running on it. Each SA is connected to the manager server of the unified platform through LAN. The master agent, which runs on the manager server, receives information from every subnet by exchanging information with each SA, and converts the pattern of received information into the sharing pattern of WAN-based monitoring and diagnosis system.

2.2.3. Information structure design

The overall information structure is divided into two tiers, MANAGER adopts MIB technology, the core database system uses common relational database systems and the information exchange is implemented by network based common query language SQL. Since the fieldbus often adopts DDE or OPC technology for information integration, besides referring to the above information structure, the core database should also take into consideration the operations that are suitable for the monitoring and diagnosis system. Meanwhile, the core database should have the capacity to be converted into the information base structure suitable for web browsing. The basic configuration of the core database of monitoring and diagnosis system is shown in Fig. 4.

The unified integrated platform based on embedded fieldbus is shown in Fig. 5. The whole platform is composed of universal gateway management station, historical database, Ethernet, universal gateway and various fieldbus networks. The communication between universal gateway

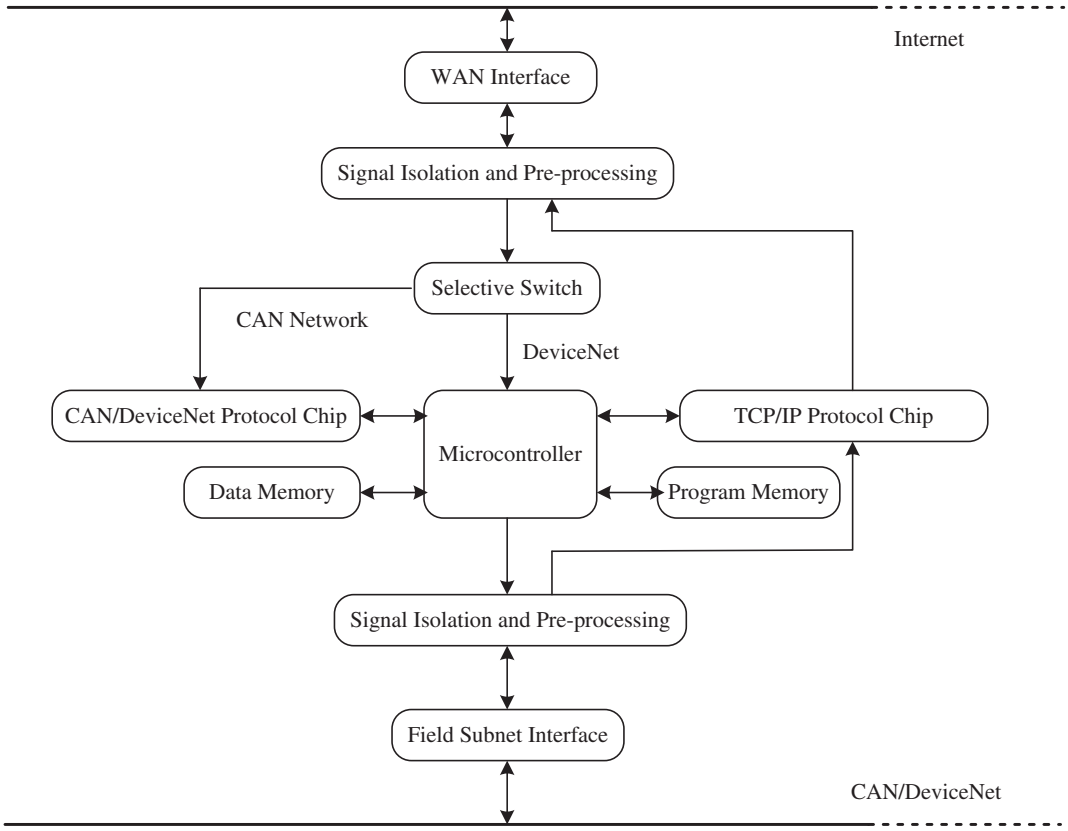


Fig. 3. The structure of embedded fieldbus gateway.

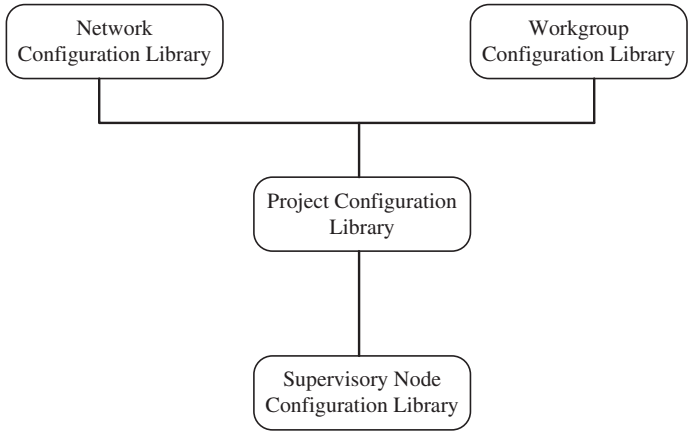


Fig. 4. The configuration structure of core database.

management station and every universal gateway is based on SNMP (simple network management protocol) and network management software is applied to manage the entire network. Hence, the remote monitoring and real-time analysis of working conditions can be realized while the automatic systems can be seamlessly integrated into the enterprise management systems. Consequently, the unified integrated platform for monitoring and diagnosis has wide-range compatibility and good extensibility.

3. Embedded high-speed signal demodulation and processing system based on FBGS

As mentioned in Section 1, FBGS is superior to other sensors in terms of immunity to electromagnetic interferences, size, and tolerance to the working environment, while the embedded system plays an extremely important role in the modern mechanical engineering. Therefore, FBGS technology together with embedded technology

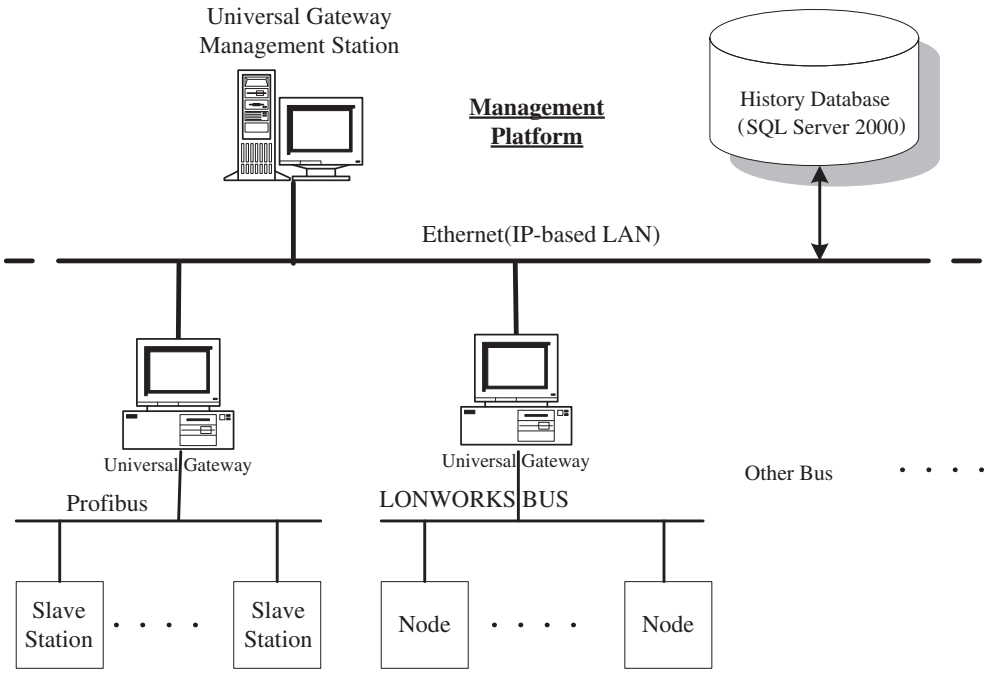


Fig. 5. The integrated platform based on embedded fieldbus.

could be further developed for the intelligent monitoring and fault diagnosis of MME. However, in FBGS application, it is a challenge to acquire the real-time data from mechanical components that work under severe environment (e.g. high speed, high temperature, high pressure, or overloading) [4]. Aiming at this problem, the most important issue is to develop a high-speed demodulation and data transmission system to meet the requirements of distributed multi-parameter monitoring, synchronous sampling, and long-term dynamic monitoring. Consequently, the basic theory and key technology for high-speed demodulation, data transmission and processing are discussed in this section [7].

3.1. Real-time detection and high-speed demodulation calculation of high-speed FBG photoelectric conversion

For the high-speed and high-precision FBG demodulation system based on F–P filters, a key technology is the high-speed and real-time detection of electrical signal transformed by the reflected light of Bragg grating through a photo-detector. Fig. 6 illustrates the structure of the high-speed FBG signal detection module.

To settle the conflict between the real-time and high-speed signal processing, both the hardware and software methods are adopted to improve the de-modulation speed and the signal processing ability. The hardware includes FPGA, DSP and SOPC on-chip-system while the software methods include the piecewise linear interpolation algorithm and piecewise peak-seek algorithm, which are adopted to analyze and process the data derived from a scanning period of the system. Based on these two methods, the goals of high-speed and real-time signal processing are achieved. In order to overcome the disadvantages of traditional demodulator, the DSP (digital signal processing) technology and high-speed programmable logistic devices are employed to implement the FBG signal detection. Compared with the single-chip microcomputer, both the calculation speed and the calculation precision of digital signal processor are greatly improved, due to the reason that it has the specialized hardware and operation commands for mathematical calculation, as well as the upper-40-bit operation registers. Moreover, FPGA (field-programmable gate array) can meet the requirements of high-speed digital signal processor for high-speed temporal logic and combinational logic. Further more, it allows signal pre-processing, enables the DSP chip to run at highest frequency, and fully displays the predominance of the digital signal processor. Taking the advantages of DSP, we adopt the real-time detection using multi-channel wavelength division grating in F–P filters' scanning rising edge, and the demodulation algorithm of wavelength in F–P filters' scanning falling edge.

3.2. Transmission and networking of mass real-time data

During the practical application process, a demodulator is usually used to demodulate the multi-channel Bragg grating. On this occasion, mass wavelength data would be produced when the demodulation speed is very high. Therefore, how to transfer the wavelength data derived from each grating in a real-time manner but avoid the system congestion is a new problem that needs to be addressed when developing the high-speed demodulator. Furthermore, with the development of information technology and intelligent monitoring technology, the test

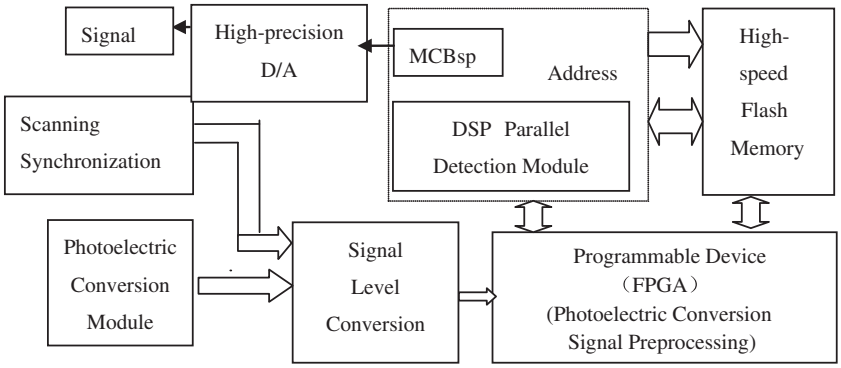


Fig. 6. High-speed signal detection module.

instruments always need to be connected to the LAN of the monitoring system, to implement data sharing and centralize remote monitoring. Hence, the monitoring instrument networking is a new development trend of online real-time intelligent monitoring [8].

In order to avoid the affection of DSP's demodulation resources, the advanced 32-bits ARM (advanced RISC machine) micro-controller is adopted for the transmission and scheduling of demodulation data. High-speed dual-port ARM is employed to transmit data for ARM microcontroller system and high-speed DSP system. The ARM microcontroller, combined with the third-generation embedded Ethernet card chip, is selected to form a 10 M/100 M adapting Ethernet card. Meanwhile, the networking function of the demodulator can be realized by designing the embedded TCP/IP protocol stack. Therefore, the mass demodulation data would be exactly sent to the target computers in a real-time manner via the Ethernet. Moreover, in order to improve the adaptability of the system, two reserved communication ports—USB and RS232 are added to the system. Since the BGD-4M40 high-speed FBG demodulator can run in the long-term and consecutive way, the network data can be reliably and continuously transmitted by the self-designed network system [9].

3.3. Embedded high-speed signal demodulation theory and technology

3.3.1. High-speed FBG demodulation principle

During the demodulation process, the wave-length of each measuring point can be calculated by using the comparative relationship between the measurement channel point and the referred channel point. If the cavity length of F–P cavity is proportional to the tuning voltage which is linear, the wavelength of reflected wave (denoted by λ) is proportional to the scan time t. The relationship between the tuning voltage and the reflected wavelength is shown in Fig. 7.

As shown in Fig. 7, the relationship between tuning voltage and the reflected wavelength is defined as

$$\lambda = at + b \tag{1}$$

where a and b are constants which can be obtained based on the practical experiment. Eq. (1) indicates that the wavelength detection resolution is proportional to the time measurement resolution.

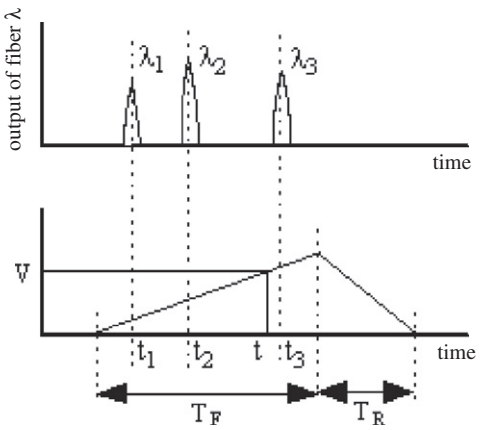


Fig. 7. Relationship between tuning voltage and the wavelength of reflect wave.

If λ_1, λ_2 and λ_3 denote the wavelengths of three reflected waves, and t_1, t_2 and t_3 are their corresponding scan times, Eqs. (2) and (3) can be defined based on Eq. (1):

$$\lambda_2 - \lambda_1 = b(t_2 - t_1) \tag{2}$$

$$\frac{\lambda_2 - \lambda_1}{\lambda_3 - \lambda_2} = \frac{t_2 - t_1}{t_3 - t_1} \tag{3}$$

Eq. (2) indicates that the wavelength difference of reflected waves is proportional to their corresponding scanning time difference while Eq. (3) indicates that the ratio of wavelength difference of reflected waves is proportional to the ratio of their corresponding scanning time difference.

If the detection range of wavelength is λ_L and the required wavelength demodulation resolution is γ_λ, then the required resolution of time measurement is

$$\gamma_t = \frac{\gamma_\lambda}{\lambda_L} T_F \tag{4}$$

where T_F is the forward scanning time.

When T_R is the return scanning time, the scanning frequency f_T is defined as

$$f_T = \frac{1}{T_F + T_R} \tag{5}$$

If the ratio of the forward scanning time and the return scanning time $T_F/T_R = 1/C$ is a constant (if the scanning frequency f_T is 2000HZ, due to the performance limitation of F–P cavity, T_F/T_R is set to 3/2 and $C = 2/3$), then the relationship between the wavelength demodulation resolution γ_λ, the wavelength detection range λ_L (which is always defined as 50 nm), the time measurement resolution γ_t and the scanning frequency is defined as

$$\gamma_\lambda = (1 + C)\gamma_t \lambda_L f_T \tag{6}$$

According to Eq. (6), if $C = 2/3$, $\lambda_L = 50$ nm, the required scanning frequency f_T is 2000 HZ and the required wavelength resolution γ_λ is 1 pm, then the time measurement resolution γ_t must be achieved around 6 ns, which means that the data sampling frequency of the demodulation system must reach 167 M. Since the processing capability of SOPC on-chip-system can achieve 200 M, the scanning frequency of our system is possible to exceed 2000 HZ, and the wavelength demodulation resolution is possible to achieve 1 pm as well.

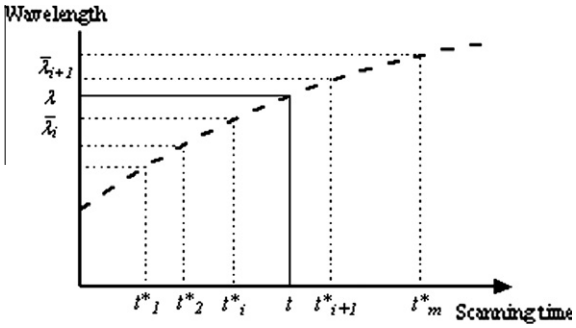


Fig. 8. Piecewise linear processing of wavelength demodulation.

3.3.2. Piecewise linear interpolation algorithm

As mentioned previously, Eq. (6) is deduced based on the condition that the cavity length of F–P cavity is proportional to the tuning voltage which is linear. However, there are many nonlinear factors existing in the practical engineering applications which will affect the demodulation resolution. With the consideration of nonlinear factors, several FBGs with standardized wavelength are deployed for reference and the piecewise linear interpolation algorithm is adopted to calculate the wavelength of the measurement points.

Suppose $\bar{\lambda}_1, \bar{\lambda}_2, \ldots, \bar{\lambda}_i, \bar{\lambda}_{i+1}, \ldots, \bar{\lambda}_m$ are the reflected wavelengths of the standardized reference FBGs which can be measured in advance, $t^*_1, t^*_2, \ldots, t^*_i, t^*_{i+1}, \ldots, t^*_m$ are the measured times of the reflected wave during the wavelength scanning process, and t $(t^*_i \leqslant t \leqslant t^*_{i+1})$ is the measured time of a reflected wave whose wavelength λ is unknown. The following equation can be defined according to Eq. (3):

$$\frac{\lambda\bar{\lambda}_i}{\bar{\lambda}_{i+1}\bar{\lambda}_i} = \frac{t - t^*_i}{t^*_{i+1} - t^*_i} \quad (t^*_i \leqslant t \leqslant t^*_{i+1}) \tag{7}$$

Hence, the unknown wavelength λ can be determined by

$$\lambda = \frac{\bar{\lambda}_{i+1} - \bar{\lambda}_i}{t^*_{i+1} - t^*_i}(t - t^*_i) + \bar{\lambda}_i \quad (t^*_i \leqslant t \leqslant t^*_{i+1}) \tag{8}$$

The piecewise linear processing of wavelength demodulation is shown in Fig. 8.

Therefore, by adopting the piecewise linear interpolation algorithm, the measurement error led by the

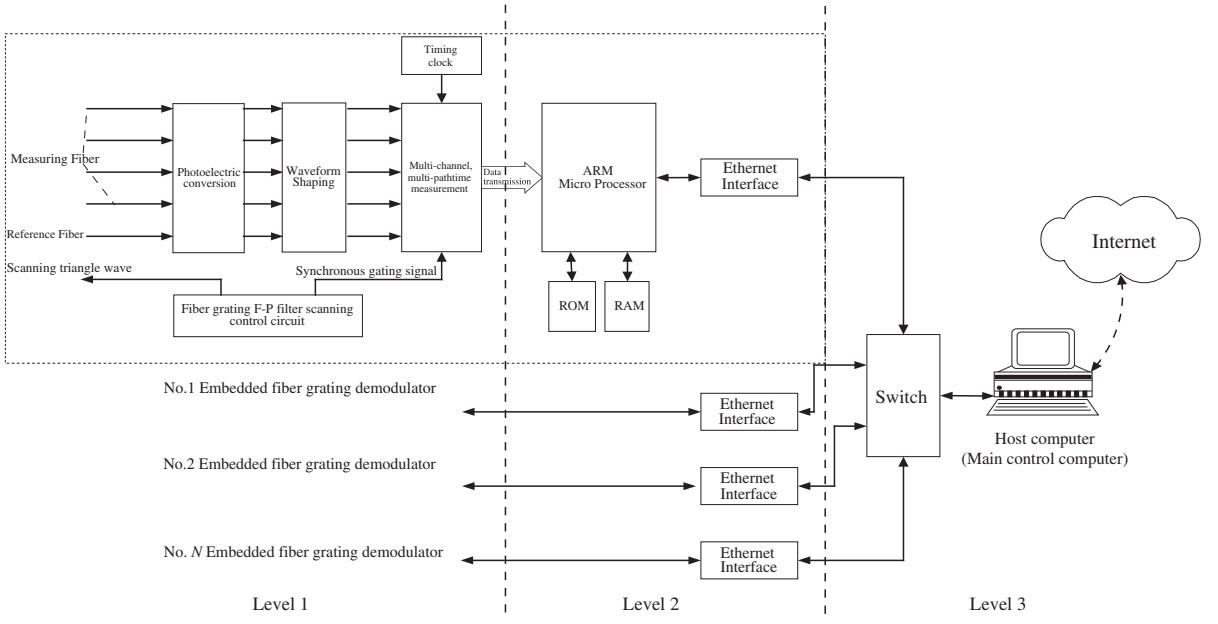


Fig. 9. Structure of the multi-channel, multi-point FBG embedded high-speed demodulation system.

nonlinearity and instability of the demodulation system can be effectively reduced, which can be controlled within ±4 pm.

3.4. Embedded high-speed demodulation system for multi-channel and multi-point FBG

Fig. 9 demonstrates the basic structure of the distributed high-speed multi-channel, multi-point FBG demodulation system based on embedded technology. As high-speed multi-channel, multi-point measurement will bring tremendous data flow, the whole system is divided into two parts which are the embedded FBG sensing demodulator for field measurements and the upper monitor (PC, master computer). Embedded FBG sensing demodulator is designed as a specialized embedded system which is unmanned, remote controllable and consecutively workable. As shown in Fig. 9, the reflected pulse of multi-channel FBG is detected at a high-speed, and the detected data are simply processed by the embedded system. Then, the data are sent to the upper monitor system through high-speed Ethernet. The high-speed multi-channel pulse detection, data processing and communication control are divided into two embedded subsystems, while a number of embedded FBG demodulators communicate with the upper monitor system through a switch. These embedded demodulators are controlled by the upper monitor system through network, and the data demodulated by them are sent to the upper monitor system for storage, analyzing, and displaying. Thus, a distributed multi-point FBG demodulation system is constituted. Furthermore, since the whole demodulation system can be either connected to the Internet or other networks through the upper monitor system, or integrated into the large-scale distributed measurement or monitoring platforms, the embedded demodulators can be agilely configured [10].

In the embedded high-speed demodulation system mentioned above, the FBG wavelength self-calibration demodulation algorithm is determined by the following two steps.

The first step is the basic relations between FBG wavelength self-calibration values. Fig. 10 demonstrates the model of signal processing. As shown in the figure, if the input signal is x and the output signal is y, the signal processing sensitivity g is defined as

$$g = \frac{y}{x} \tag{9}$$

Therefore, the signal conversion relationship of FBG sensing demodulation is defined as follows:

$$\begin{aligned} Y &= G \times X \\ &= g_1 \times g_2 \times \cdots \times g_n \times X \\ &= g_1 \times (g_2 \times g_3 \times \cdots \times g_{k-1}) \times (g_k \times g_{k+1} \times \cdots) \times \cdots \times X \end{aligned} \tag{10}$$

$$G = g_1 \times g_2 \times \cdots \times g_n \tag{11}$$

In Eq. (10), Y is the final output value of the demodulation system, X is the measured physical value, G is the total sensitivity of the FBG sensing demodulation process, and g_i ($i = 1, 2, \ldots, n$) is the sensitivity of each sub-process.

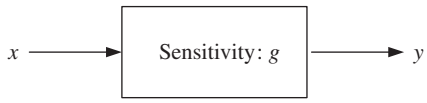


Fig. 10. Signal processing model.

As indicated in Eq. (10), there are three ways to figure out the value relation between the demodulation output and the measured physical quantities: (1) by obtaining all the procedures which process and affect the signals and their sensitivities g_i, (2) by obtaining the sensitivity of each sub-process, or (3) by obtaining the total sensitivity G of the system

The sensitivity of FBG wavelength demodulation subset is designed as a constant digital output corresponding to the certain input wavelength (e.g. 1 pm). Since this subset is independent of the type or sensitivity of the sensor, it can be used in a general way. When different physical quantities or fiber sensors with different sensitivities are processed, the measured physical quantities are attained by connecting the processing data with their corresponding sensitivities.

The method described above can be implemented by adding a sensitivity normalization process to each subset. If X' and Y' are the input and output of FBG wavelength modulation subset, respectively, G' is the total sensitivity, $g'_1, g'_2, \ldots,$ and g'_{j-1} are the constant sensitivities of the signal processing processes of the corresponding subsets, g'_j is the normalized adjustment process sensitivity. Obviously, G' can be set to an expectation value by adjusting g'_j. The relation between X' and Y' is described as

$$Y' = G' \times X' \tag{12}$$

$$\text{where} \quad G' = g'_1 \times g'_2 \times \cdots \times g'_j \tag{13}$$

The second step is the self-calibration demodulation of FBG wavelength. In an ideal measurement system, both the sensitivity of each procedure during the signal processing process and the sensitivity of the whole system are independent of the input signal and time, which means that its input and output satisfy the constant linear relationship. However, in FBG demodulation process, due to the voltage control characteristic of the tuning F–P cavity, the nonlinear characteristic of scanning voltage, and the instable characteristic of counting clock etc., the practical demodulation system may be a nonlinear and time variable system whose signal transformation is characterized by nonlinearity and instability. For instance, the typical wavelength tuning repeating error of the tunable F–P cavity is around 0.1–1.0 nm. Obviously, if this kind of error is not eliminated, the measurement accuracy of the sensing quantities would be significantly affected. In order to eliminate the wavelength demodulation error brought by the system's nonlinearity and instability, the piecewise linear, real-time and self-calibration method is adopted. This method can be realized by settling a fiber with a number of standard reference FBGs into the demodulator, and connecting it to a detection channel which is the same as the measured one. During the scanning process, this detection

channel along with four measuring channels will be simultaneously detected by the demodulator. The standard reference FBG is a standard FBG whose wavelength is strictly measured.

4. Integrated intelligent monitoring and diagnosis system based on embedded and FBGS technologies for modern heavy duty mechanical equipment

In order to monitor the operation state of modern heavy duty mechanical equipment, such as engine vibration, stress–strain characteristic, piezoelectric vibration sensors and strain gauge sensors are generally employed. These methods always install dozens or hundreds of sensors on the machinery shell and accessories to measure the vibrations or dynamic strains. However, such traditional methods have obvious disadvantages due to the following reasons: (1) the measuring positions are insufficient; (2) the electronic sensors are always seriously affected by the environmental interfering; (3) the strain gauge is short-life; and (4) the online machine measurement is very difficult to be realized. In addition, through the traditional methods, some contact surfaces or perturbation parts are impossible to test. For example, while testing the pipe, only the measurement of its wall is practical, but the measurement of its temperature field is impossible. Moreover, because the traditional methods adopt the radio to transmit the sensing signals collected from heavy duty or complex mechanical equipment, it is vulnerable by the restriction of power supply and the interference of electromagnetic field. Therefore, constrained by the measurement method, the comprehensive analysis of influence factors and vibrations is very hard to be implemented. For the intelligent monitoring and diagnosis of heavy duty mechanical equipment, the more direct measurement parameters and realistic data are obtained, the more correct analyses are possibly achieved [11].

4.1. System integration method based on embedded and FBGS technologies for MME

The method of embedded system integration for intelligent monitoring and diagnosis system is shown in Fig. 11. The first step is to analyze the requirement of the target MME, such as the structure, the measured physical quantity, and the environment. The second step is the monitoring method analysis, i.e. the sensing mode, the measuring point planning, and the information process. The third step is the software definition and assigning, and then an optimized intelligent monitoring and diagnosis integration system is constituted. By using this method, an intelligent monitoring and fault diagnosis system for large-scale tipper based on FBGS and embedded technology is developed, whose architecture is shown in Fig. 12 [12].

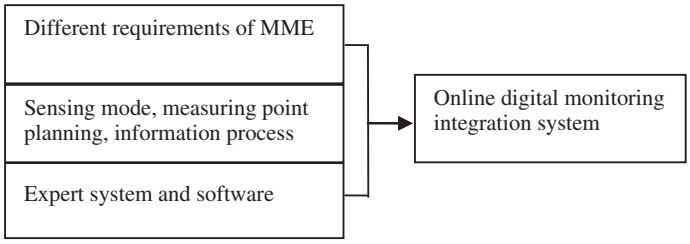


Fig. 11. System integration method.

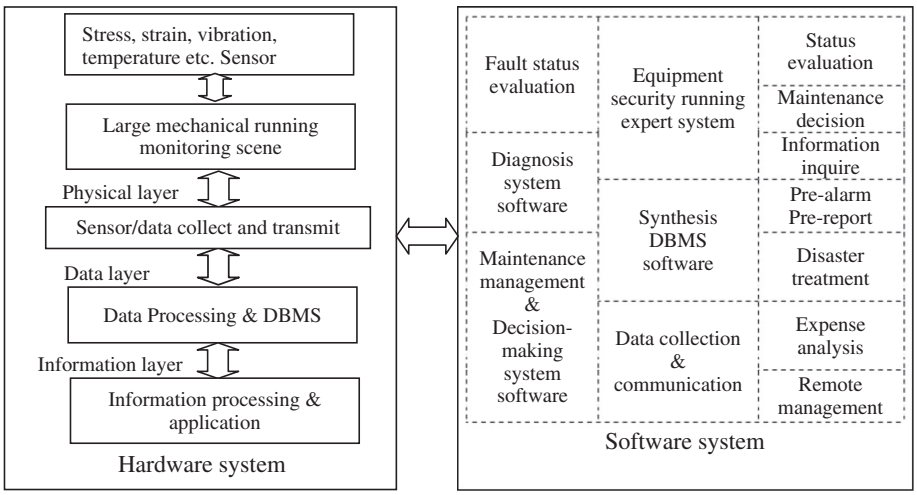


Fig. 12. Digital monitoring and fault diagnosis integration system.

Fig. 13. The structure of large-scale tipper in Qinhuangdao port.

From Fig. 12, we can see that, the detailed configuration of both the hardware and the software of embedded integration system are determined. The hardware system mainly includes three layers, i.e. physical layer, data layer and information layer. Among them, FBG sensors, data collector, information processing instrument, sensor/data collect and transmit are employed. The software system consists of a number of modules, such as fault status evaluation [13], data collection and communication, information analysis and processing, expert diagnosis and decision-making, pre-alarm, pre-report and remote management.

4.2. Integration architecture based on embedded and FBGS technologies for intelligent monitoring and diagnosis of large-scale port tipper

The research is carried out through the embedded integration and hardware implementation of online intelligent monitoring system with distributed multi-parameter, which combines embedded and FBG sensing technologies. These technologies include the sensing mode, data processing, dynamic characteristic identification,

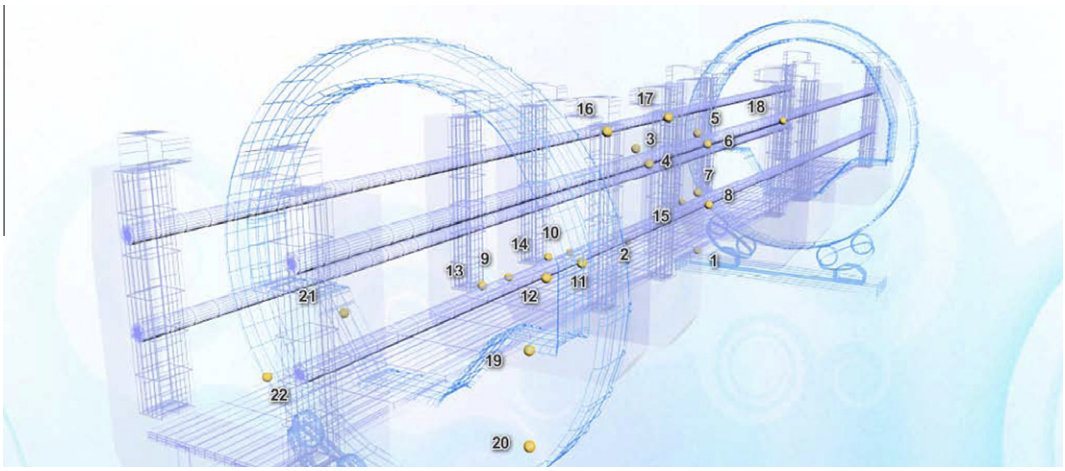


Fig. 14. The installation positions of 22 embedded FBGSs installed into the large-scale tipper.

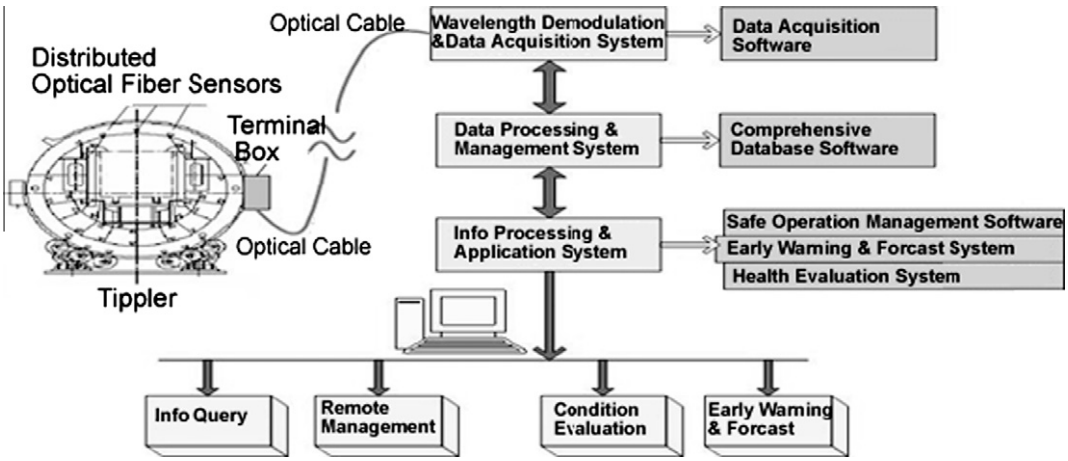
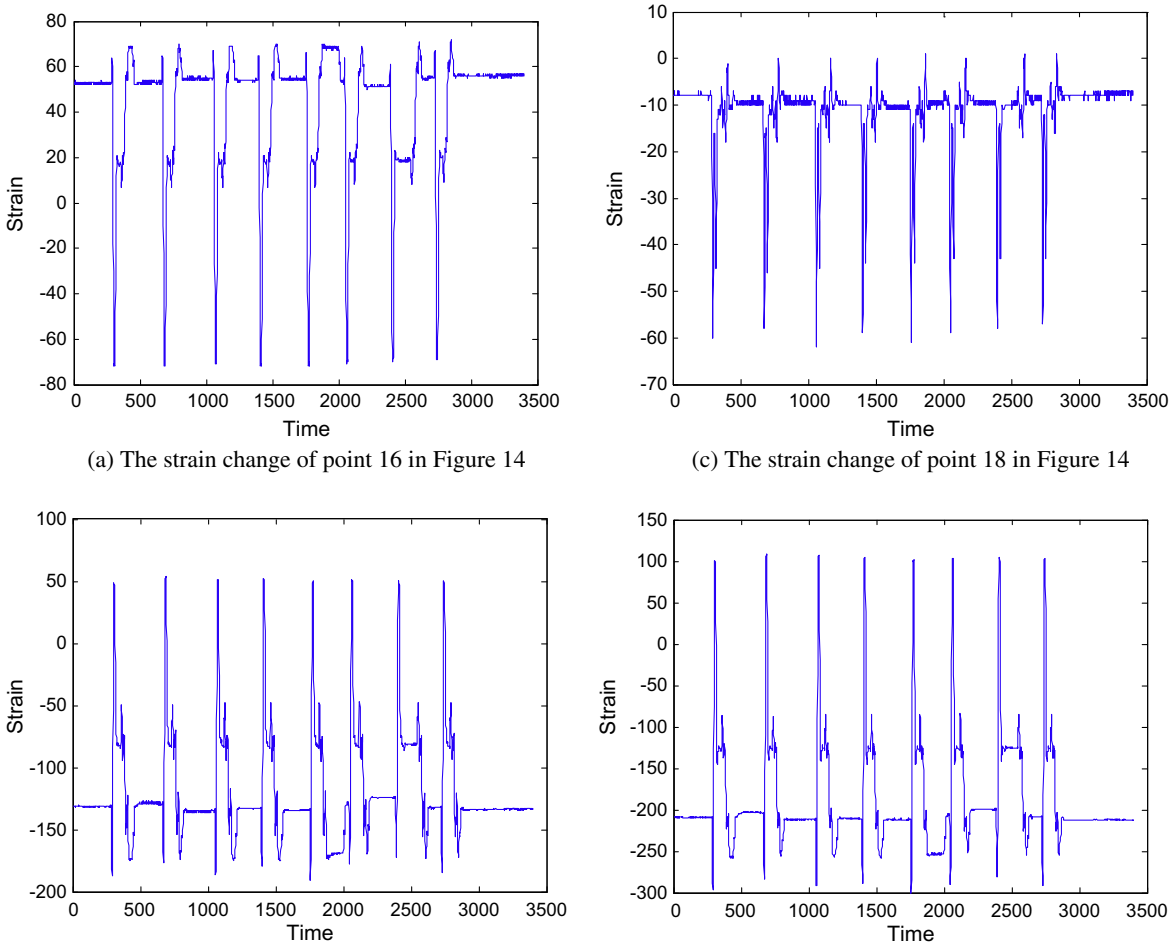


Fig. 15. The architecture of intelligent monitoring and diagnosis system for large-scale tipper based on FBG sensing and embedded technology.



(a) The strain change of point 16 in Figure 14

(c) The strain change of point 18 in Figure 14

(b) The strain change of point 3 in Figure 14

(d) The strain change of point 4 in Figure 14

Fig. 16. The strain changing curves of point 16, 3, 18, 4 showed in Fig. 14.

human–machine interface, visualization method, hardware implementation, and so on. For instance, the large port tipper consists of two U-shape frames, a front beam, an end beam, a bottom beam, a clamping beam, a backboard, a support roller, etc. The tipper structure is characterized by complex force conditions which include the self-weight and counterweight, self-weight of the tipper and materials, hydraulic clamping force, self-weight of the hydraulic system and so on. Therefore, the finite element model is established to analyze these forces. For the load of main steel structure, apart from self-weight that is calculated by program, other load (including the wheel pressure produced by tipper and materials, the self-weight of hydraulic system, the force of the backboard's support bar, the gravity and clamping force of clamping hook, the cylinder force of backboard, the gravity of baluster and guide sleeve of clamping hook etc.) are all analyzed based on the established model of the tipper. Through the model, the measuring points can be located, the key force bearing points can be found and the sensor installation to the corresponding parts of tipper can be completed. According to the force distribution state, the research on unidirectional way, bidirectional way (in rectangle), and tri-directional way (in strain rosette) of embedded FBG strain sensors has been carried out.

As an example, the composite stress is calculated firstly. FBGS acquires the strain value from the measuring points which consist of single point, rectangular point and strain rosette categorized by the points and different sensors. The single point means only one strain sensor is embedded at each measuring point, and the rectangular point means two strain sensors are embedded at each measuring point to form rectangle embedded sensors, while the strain rosette means three strain sensors are embedded at each measuring point. The stress calculated formulas of the three kinds of points are described as follows.

(1) Single point

$$\sigma = 0.206 \times \varepsilon \tag{14}$$

where σ is the calculated stress value, ε is the strain value of the single point embedded FBG sensor.

(2) Rectangular point

$$\sigma = \frac{1}{2}\left[\frac{E}{1-\mu^2}\times(\varepsilon_1+\mu\varepsilon_2)+\frac{E}{1-\mu^2}\times(\varepsilon_2+\mu\varepsilon_1)\right] \times\left(1+\cos 2arctg\frac{\frac{E}{1-\mu^2}\times(\varepsilon_1+\mu\varepsilon_2)}{\frac{E}{1-\mu^2}\times(\varepsilon_2+\mu\varepsilon_1)}\right) \quad (15)$$

where σ is the obtained strain value, $E = 0.206$, $\mu = 0.3$, ε_1 and ε_2 denote the strain values of the two embedded FBG sensors which form a strain rectangular.

(3) Strain rosette

$$\sigma = \frac{E}{2}\left[\frac{\varepsilon_1+\varepsilon_3}{1-\mu}+\frac{1}{1+\mu}\sqrt{(\varepsilon_1-\varepsilon_3)^2+(2\varepsilon_2-\varepsilon_1-\varepsilon_3)^2}\right] \quad (16)$$

where σ is the obtained strain value, $E = 0.206$, $\mu = 0.3$, ε_1, ε_2 and ε_3 indicate the strain values of the three embedded FBG sensors which form a strain rosette.

According to the operation data and theoretical model of the port tipper, the distributed parameter measurement and the effective status analysis are achieved, the running error of the tipper can be detected in real-time manner, the potential failure of the tipper is avoided, and thus the bottleneck of heavy material field port is overcome. Consequently, the research of this section can be applied to the distributed online monitoring and state evaluation (e.g. stress, strain, temperature, health status) for tipper used in metallurgy industry, power generation, chemical industry, and large-scale port.

To follow the ideas mentioned above, 22 embedded FBGSs were installed into the two end rings of the U-shape frame, the front beam, the end beam, and the bottom beam of a large-scale tipper in Qinhuangdao Port, China (as shown in Figs. 13 and 14). As a result, the long-term intelligent monitoring for tippers of the port was implemented. The architecture of the intelligent embedded monitoring system for that tipper is shown in Fig. 15. The axial strain changing curves of point 16, 3, 18, 4 marked in Fig. 14 are shown in Fig. 16a, b, c and d, respectively. Taking Fig. 16a for example, it indicates the dynamic strain change of point 16 during eight tipping periods of the tipper. Therefore, by analyzing these FBG sensing data, not only the real-time state of the tipper can be detected and the running security of the tipper can be guaranteed, but also the investment to the tipper can be greatly saved. In addition, the system has been successfully applied to monitor for other large mechanical equipment of other port, such as the quayside container crane and 2000-ton large floating crane.

5. Conclusions

Comparing with the traditional sensing monitoring and diagnosis methods, the application of embedded technology and FBG sensing technology to the intelligent monitoring and diagnosis for MME is a revolutionary innovation, especially for the monitoring of heavy duty mechanical equipment which works under the extreme condition and environment (e.g. high temperature, high pressure and over loading condition). The methodologies and system proposed in this paper are superior to the traditional ones due to their following advantages: (1) the proposed monitoring and diagnosis equipment has small volume which is easier to monitor the narrow space structure; (2) it can transmit long distance signals and has good stability and environment adaptability; (3) it employs wavelength encoding method which has good ability of anti-electromagnetic interference; (4) it can implement multi-parameter, online, distributed, and long-term monitoring and diagnosis; (5) it has good intelligence by developing the system based on the integration of embedded technology and FBGS technology. The main contributions of this paper are as follows.

- The interconnected logical structure and network architecture of the monitoring and diagnosis system based on embedded technology are presented, the embedded fieldbus gateway for the integration of monitoring and diagnosis system and the integrated platform based on embedded fieldbus are developed.
- The high-speed demodulator for signal processing and data transmission system based on the integration of embedded technology and FBGS technology is developed, which can meet the requirements of distributed multi-parameter monitoring, synchronous sampling and long-term dynamic monitoring.
- The intelligent monitoring and fault diagnosis integration system for actual modern heavy duty mechanical equipment based on FBGS technology and embedded technology is proposed.

Since the research of this paper is a multi-disciplinary research area which must assimilate the latest theory and technology, it still leaves many problems needed to be further solved, such as the new FBGS and high performance demodulation system, high-speed signal processing and transmission, sensing head design and sensor distribution planning, system integration, and intelligent fault diagnosis. Nevertheless, it could be predicted that with the development of FBG sensing technology, embedded technology, information engineering, and material science, the research on the integration of embedded technology and FBG sensing technology will make great contributions to the modern intelligent monitoring and diagnosis technologies, especially to the mechanical monitoring and diagnosis science and engineering.

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