Strain monitoring of railway bridges using optic fiber sensors

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Abstract

Purpose – The purpose of this article is to suggest that Fraby-Perot optic sensor is a practical measurement gage to monitor the strain of great structures such as railway bridges.

Design/methodology/approach – A remote strain monitoring system based on F-P optic fiber and virtual instrument is designed to monitor the strains of a railway bridge.

Findings – The application results show that the Fraby-Perot optical fiber sensors can accurately measure strain and they are suitable for the long-term and automatic monitoring. In addition, the system has several advantages over conventional structural instruments including fast response, ability of both static and dynamic monitoring, absolute measurement, immunity to interferences such as lightning strikes, electromagnetic noise and radio frequency, low attenuation of light signals in long fiber optic cables.

Practical implications – Health monitoring of structures is getting more and more recognition all over the world because it can minimize the cost of reparation and maintenance and ensure the safety of structures. A strain monitoring system based on F-P optic fiber sensor was developed according to the health monitoring requirements of Wuhu Yangtze River Railway Bridge, which is the first cable-stayed bridge with a maximum span of 312 m carrying both railway and highway traffic in China. It has run stably in the monitoring field more than two years and fulfilled the monitoring requirement very well. Now the system has been transplanted successfully to the Zhengzhou Yellow Railway Bridge for strain monitoring. So the work can be referenced by other similar health monitoring projects.

Originality/value – Long-term, real-time monitoring of strain using FP fiber optic sensors in railway bridge is an innovation. A remote strain data acquisition and real-time processing are another character of the system. The work studied can be referenced by other structures monitoring, such as tunnel, concrete bridges, concrete and earth dams.

Keywords Fibre optic sensors, Bridges, System monitoring,

Paper type Research paper

1. Introduction

Many of the structures, especially bridges, need to be repaired or replaced because of their age. In order to minimize the cost of reparation and maintenance and to ensure the

This work was supported by Grant-Aid for Wuhu Yangtze River Bridge health monitoring (No. 2000G019) from Railway Ministry of PR China.

Journal of Quality in Maintenance Engineering
Vol. 13 No. 2, 2007
pp. 186-197

1355-2511
DOI 10.1108/13552510710753087

safety of civil infrastructures, there is an increasing need for health monitoring of structures all over the world (Housner *et al.*, 1997; Zhang, 2000; Hong-Nan *et al.*, 2004). Structural health monitoring (SHM) refers to the use of in-situ, continuous or regular (routine) measurement and analyses of key structural and environmental parameters under operating conditions, for the purpose of warning impending abnormal states or accidents at an early stage to avoid casualties as well as giving maintenance and rehabilitation advice (Housner *et al.*, 1997). For medium span railway bridges, the train is the main load of the bridge structure. Therefore, the health monitoring system for railway bridges is mainly to monitor the dynamic response (includes the vibration displacement, acceleration, strain, deformation of bridges) when trains passing on bridges. And the strain is one of the most important parameters that reflect the bridge's health state. In order to learn the working state and safety of a structure, it is necessary to monitor the strain/stress of the structure under the action of loads.

Structural health monitoring typically involves measuring the strain that a structure undergoes different loads. Strain is defined as the fractional change in length of a structural member due to the force acting on it. It is given by $\Delta L/L$, where L is the original length of the member and ΔL is the resulting change in length. Most of the conventional sensors used in strain monitoring applications are based on transmission of electric signals. Their limitations are becoming more and more manifest. These sensors are usually not small or durable enough to be embedded in a structure to measure interior properties. They are local (or point) sensors, which are restricted to measure only parameters at one location and cannot be easily multiplexed. The long lead lines also pose problems for large civil structures, which often span several or tens of kilometers. In some cases, the signals could not be discriminated from noise because of electrical or magnetic interference (EMI). In addition, various demodulation techniques are required for different sensors. All the above add in increasing the inconveniences of conventional sensors in SHM. Fiber optic sensors (FOSs) are promising sensing alternatives in civil SHM systems and future smart structures. They exhibit several advantages such as, flexibility, embeddability, multiplexity and EMI immunity, as compared with traditional sensors (Choquet *et al.*, 1999; Clark *et al.*, 2001; Lengm and Asundi, 2003; de Oliveira *et al.*, 2004).

In recent years, Fabry-Perot optic fiber sensors are used for structural monitoring of large civil structures such as dams, bridges, buildings and composite material structures widely due to its unique features. These sensors can be attached to the surface or embedded into materials and structures to monitor conditions such as damage, strain, stress, crack formation, pore pressure and temperature continuously. The absolute extrinsic Fabry-Perot interferometer (EFPI) is one of these sensors. This sensor has the inherent advantages of many fiber optic sensors like small size, light weight, non-conductivity, fast response, resistance to corrosion, immunity to electromagnetic noise and radio frequency interferences eliminating the need for costly and bulky shielding and lightning protection accessories (Hong-Nan *et al.*, 2004). It can sense a variety of physical effects such as pressure, strain, temperature and displacement. Its small size allows them to be incorporated in composite material without sacrificing structural integrity. When it is used in the measurement, a common multimode optical fiber is needed to carry the signal to the readout units. The data from the read unit can be taken manually or permanently connected to a computer through RS-232 link. While the benefits of long term structural monitoring are yet to be fully realized.

A case of long-term strain monitoring of a railway bridge with Fabry-Perot sensor is studied and implemented. In order to suit the requirement of long-term and real time monitoring, a remote strain data acquisition system is designed. The data and information acquired is transported through optic cable to the control room. The system is able to control the instrument and readout equipments at any moment to get the data needed and process the data automatically. Both static and dynamic measurements can be realized with this system. Some results of laboratory and field tests are presented.

2. Fabry-Perot optic fiber sensors

2.1 Measuring principle

An optic fiber sensor system basically consists of a light transmitter, a receiver, an optical fiber or bundles, a modulator element and a signal processing unit. Light is transported to the measurement point (modulator) using optical fibers or bundles and such a scheme in generally termed as extrinsic modulations. If the fiber itself acts as a sensitive element, then intrinsic modulation takes place. Several demodulation techniques such as Fizeau interferometer are available to evaluate this phase difference and relate it to strain. Optic fiber sensors can be classified under different categories. Localized, distributed and multiplexed sensors are based on sensing methods. Intensity, interferometric, polarometric and spectrometric are based on transduction mechanism (Choquet *et al.*, 1999).

The Fabry-Perot interferometric presented in this paper makes use of a broadband white light source instead of laser light. This technique can make precise, absolute and linear measurements and is quite insensitive to environmental temperature changes. The EFPI design method used to manufacture strain sensors is illustrated in Figure 1.

The sensor consists of two semi-reflective mirrors facing each other. These mirrors are placed on the tips of multimode optical fibers and these fibers are spot fused into a capillary. The air gap between the mirrors is named the Fabry-Perot cavity length (l_{cavity}) and the distance separating the fused spots is called the gage length (L_g) that indicates the gage operating range and sensitivity. A portion of white light is launched by a readout unit into one end of a fiber optic cable and travels toward the Fabry-Perot sensor. The first semi-reflective mirror reflects a portion of the white light emitted by the readout unit. The remaining light travels through the Fabry-Perot cavity and is partially reflected by the next semi-reflective mirror. The lights from the two

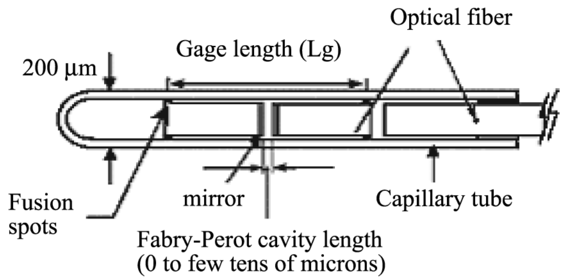

Figure 1.
Extrinsic Fabry-Perot fiber optic sensor

reflections interfere, meaning that the original white light is separated in several wavelengths and travels back to the readout unit. Cavity length (l_{cavity}) is determined instantaneously by means of an optical white light cross-correlator (Fizeau interferometer) contained in the readout unit. When the sensor is bonded to a substrate, the strain transferred to the sensor is converted into cavity length variation (Δl_{cavity}) and the strain is given by the following equation:

$$Strain(\varepsilon) = \frac{\Delta l_{cavity}}{L_g}$$

where:

l_{cavity}:	Length of the Fabry-Perot cavity, in nanometers.
L_g:	Gage length (space between in the fused weldings), in millimeters.
Δl_{cavity};	The changes of the l_{cavity}, in nanometers.
$Strain(\varepsilon)$:	Total strain measurement, in strains.

By measuring the deformation of the fiber (cavity length variation), the strain in the host structural member can be measured. Generally, the Fabry-Perot sensor is mounted at the end of a fiber optic cable to form a point sensor, but it is also possible to construct Fabry-Perot cavity in different ways in order to develop a wide range of instruments.

2.2 Signal processing technology

The conversion of optical signal into electric signal is accomplished by means of a Fizeau interferometer and a linear photodiode array combination (as shown in Figure 2) in the readout unit. This combination is also called a white light cross-correlator. The light signal reflected back by the Fabry-Perot strain sensor indicates the complete width of the Fizeau interferometer, which consists in a spatially distributed interferometer whose thickness varies from almost zero to a few tens of microns, namely exactly the same values as the minimum and maximum values of the Fabry-Perot cavity length. Light is transmitted maximally at the exact location along the Fizeau interferometer where its thickness is equal to the Fabry-Perot cavity length of the sensor (Roctest Inc., 2000). The Fizeau interferometer makes an instantaneous correlation of the signal for all spacing values of the cavity. Further processing detects

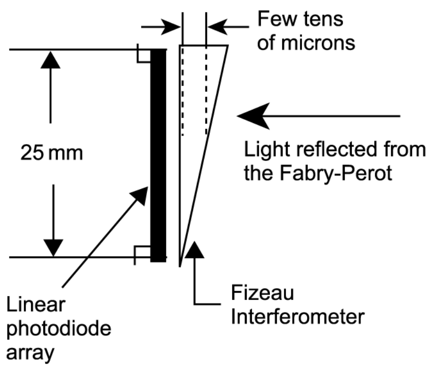

Figure 2.
Fizeau interferometer and Linear photodiode array

and locates the position of the light power peak response obtained by the linear photodiode array and determines precisely the absolute cavity length. This cavity length is absolute because it corresponds to the true cavity length of the Fabry-Perot interferometer at the time when the optical signal was measured, as opposed to a relative measurement of the cavity length in which it is determined in relation to an arbitrary zero value.

The absolute measurement is very important in applications where long term or static measurements are required in structural monitoring. The optical signal is converted in cavity length at a frequency given by the sampling rate of the readout units.

3. Calibration of strain gage

The experimental setup is shown in Figure 3. A steel girder (1500 mm × 62 mm × 9 mm) and a steel plate (426 mm × 60 mm × 12 mm) are designed to calibrate the strain gage. A F-P sensor was bonded in the middle section of the steel girder with a conventional resistive foil gage (calibrated) on the opposite side as a reference strain signal and the steel plate using for charger is put on the girder.

Figure 4 shows the comparison of the Fabry-Perot sensor and the electrical strain gage simultaneously. The graphic shows the static data obtained from the Fabry-Perot sensors and the electrical strain gage. Comparative measurements with conventional electrical strain gage are in good agreement with the Fabry-Perot sensor. The strain

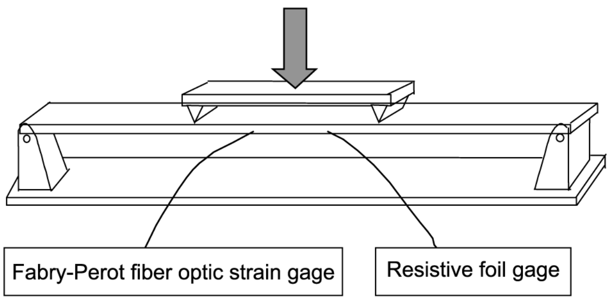

Figure 3.
The sketch of test apparatus

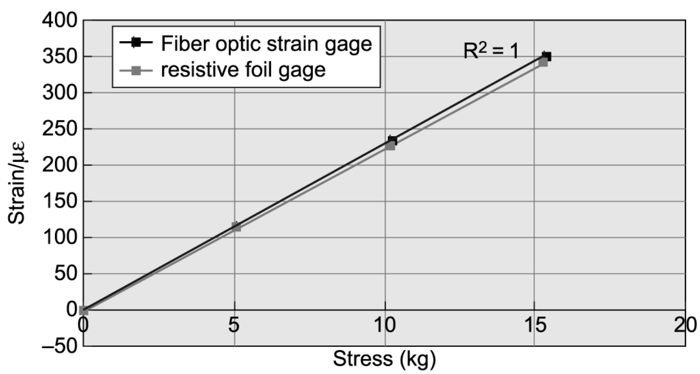

Figure 4.
Calibration result

response is linear ($R^2 \approx 1$). The strain resolution of the sensor tested is 0.01 percent full scale. The experiment is repeated several times and similar results are obtained. It can be concluded that the strain gage is of good sensitivity, linearity and repeatability.

4. Monitoring system based on F-P and LabVIEW

The Wuhu Yangtze River bridge (WYRB), as shown in Figure 5, was constructed from 1997 and commissioned in September 2000. The bridge has a double deck configuration with the expressway on the upper deck and the railway below. The whole span of the railway bridge is 10,616 meters with a main span of 2,913 meters and the whole span of the highway is 6,078 meters. The WYRB is the first cable-stayed bridge carrying both railway and highway traffic and it is the longest one up to now with maximum span of 312 m in China.

For safety assurance and maintenance, a structural health monitoring system has been devised to monitor the integrity, durability and reliability of the WYRB. This monitoring system for the WYRB comprises a data acquisition and processing system with a total of approximately 120 sensors, including accelerometers, strain gauges, displacement transducers, temperature sensors, vibration pick-ups, magnetometers, manometers, flexivity sensors and so on, permanently installed on the bridge. The whole system is installed in the field in December, 2003. The monitoring span ranges over 400 meters. The distance between the monitoring field and monitoring center is about 3,000 meters.

4.1 Monitoring spot

According to the computed results of the primary truss member's static load stress, the rules of sensors optimum layout and the practical situation of the train loads, some Spot-weldable F-P strain gages as parts of sensors in WYRB health monitoring system were installed at the bridge-deck sections as shown in Figure 6. Eight sensors

Figure 5. The Wuhu Yangtze River bridge

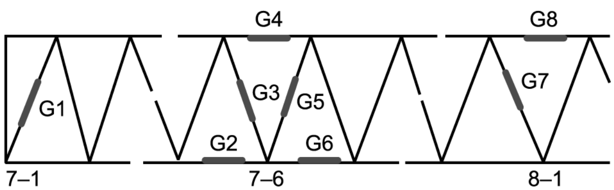

Figure 6. Monitoring spot sketch

(numbering G_1 to G_8) are mounted on the surface of the main joist members by surface-bonding technique.

The strain gage used is non-temperature compensated FOS. This kind of sensor has a small diameter of 0.20 mm and is available in various ranges. At the same time, the temperature sensors are mounted near the strain measuring spot. These temperatures measured will be used as reference to eliminate thermal strain due to the coefficient of expansion of steel. In order to suit the requirements of long-term and real time monitoring, a remote strain data acquisition system that can be controlled remotely and can work without anyone on duty is designed.

The architecture of the system is shown in Figure 7. The system includes sensor subsystem, field data acquisition and processing subsystem, remote monitoring and data transport subsystem. The data and information acquired are transported through optic cable to the control room. The system is able to control the instrument and readout equipments at any moment to get the data needed and process the data automatically. Both static and dynamic measurements can be realized with this system.

The main function of the sensor subsystem is to inspect the strain under in-service condition for the WYRB and to translate them into corresponding signals.

Data acquisition and processing system is the key and basic part of the whole system, including signal sampling, data display and preprocessing, alerting in real time and data communication. The hardware of the system consists of A/D cards, PCI bus, field monitoring computer (or MCU), RS232/RS485 interface, second-instrumentations and so on. It works in two modes. One is continuous mode. In this mode, the system works continuously, polling the command or trigger conditions and judging. Its main purpose is to get the control information for trigger acquiring. Another is triggered discontinuous data acquisition mode, in which the system acquires the structure status by the effect of the loads and circumstances (Zhan-feng *et al*, 2004). For example, the acquisition of the strains can be triggered by the coming of the train and stopped acquiring by the departing of the train. When the train passes, the system acquires the strain information of the bridge, processes the data, contrasts the result with the normal status and then judges whether the structure is normal. In addition, it can accept the command from the monitor center and take corresponding action.

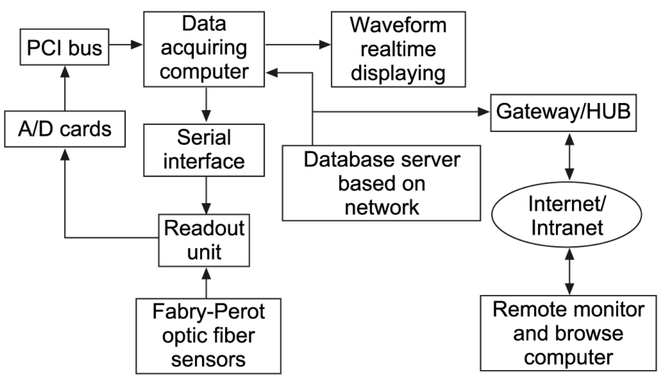

Figure 7.
Structure of the system

Remote monitoring and data transport subsystem based on the TCP/IP implements the inter-communication between the field data acquisition subsystem and the monitoring center. It can control the parameters of the data acquiring system remotely, monitor the running state of the whole system and transfer the information acquired through Internet or Web. The information acquired from monitoring spot is transmitted to remote monitoring center and stored in database in a promissory form.

4.2 Software system based on LabVIEW

As illustrated in Figure 8, the remote strain monitoring software contains three parts. The first one is field data auto-acquiring applications. The second one is remote transport and control applications. The last one is data query and analysis applications based on DBMS.

The data acquiring application running in data acquisition computer is developed on LabVIEW7.0 (Zhan-feng *et al*, 2000). Control board in microcomputer is designed according to the field fact and monitoring requirements to ensure that data acquisition parameters can be controlled and the waveform can be displayed synchronously. Multithreading technique is used to provide better system reliability when the system performs high-speed data acquisition, preprocesses the data and displays the results in real time. It controls all the sensors to start, work, stop and display the real-time waveforms of acquired data. It is initialized when the system is powered. It polls and judges the instructions from the main computer of monitoring center ceaselessly. Once a command is accepted, the application executes corresponding action. For example, it can accept the command that controls the sensor of certain location to acquire the bridge's status and send the data to data acquisition computer to display. It can also change the field parameters being assigned before. Normally, the system begins to acquire and store the status of the structure when the sampling cycle appointed by the system is reached or field trigger condition is satisfied. Once the acquired data is abnormal, the system will give an alarm to arose the attention of the keeper or watcher who can take some actions to ensure the normal running of the structure.

Remote transport and control application located on both the data acquisition computer and monitoring computer is developed on LabVIEW7.0, SQL server and TCP/IP. It has several functions. The first one is to transmit the command from the monitoring center to monitoring spot. The second one is to accept the data or

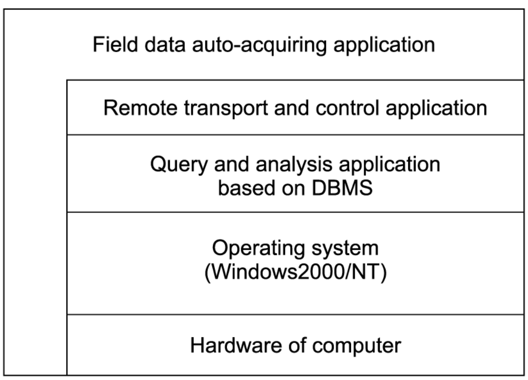

Figure 8.
Structure of the software

information from the field acquisition computer and store in the database. The last one is to see about the structure state and the system state on-line at monitoring center. In addition, the trigger modes, the sampling sequence and frequency, and the sample length of the data acquisition system can be changed by the application remotely. The working status of the system can also be diagnosed remotely.

Data analysis and evaluation application is developed on Labview7.0 and SQL Server. The functions of this application include history records query and display, data analysis, status diagnosis and print. It can display the data in graphics mode and draw the trend-line of structure status, analyze the data stored in the database according to the users' requirements, print the characteristic data, graphics and pictures, tables in which the users are interested.

4.3 Functions of the system

(1) Automatic sampling – when a train passes through the monitoring field or the trigger conditions are satisfied, the signals monitored will be sampled automatically and displayed the waveform in real-time according to the monitoring requirements.

(2) Automatic analysis and processing – the system automatically analyzes and processes monitoring data in real time and then abstracts the characteristic parameters so as to reduce a vast numbers of original data.

(3) Remote transport and automatic storing – signals from F-P sensors can be transmitted to controlling center by optic fiber over 2 km without distortion and the characteristic parameters and some raw data are automatically saved in the given database built for the WYRB.

(4) Automatic alarm – if abnormal situation occurs, the system will alarm through sound and flashing windows on the screen, and save corresponding original data permanently in database.

(5) Historic inquiry – data stored on the monitoring center can be inquired at any time.

(6) Remote control – one can visit the system, inquire monitoring data concerned or modify parameter settings through Internet according to the different authorization.

(7) High reliability and self-diagnosis – many measures are used to improve reliability of the system and the system has ability to diagnose its own fault during its running.

5. Results

These sensors and the system have been run well in the field more than two years. The system not only can control data acquisition automatically, but also can acquire data by receiving the command from the main computer of the monitoring center. Once abnormal condition occurs, the system can give an alarm to inform the maintainer and the expert to analyze the reason and take measures. Furthermore, it can transport the data and results to the main computer foe storing when every sampling procedure is over. In a word, the system realizes the purpose of real-time, online and remote strain monitoring of the bridge. In addition, history data and records are stored in database, where the data can be transplanted from one DBMS to another by using ODBC

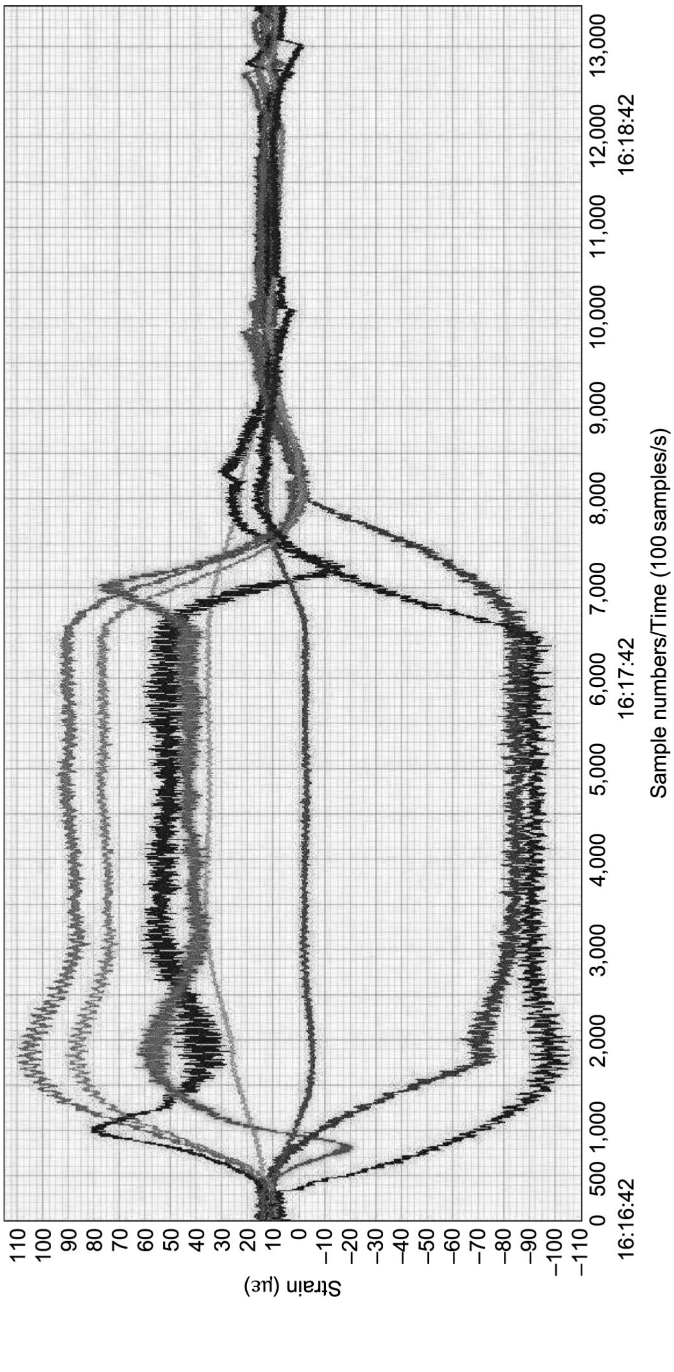

Figure 9.
Strain of pulled and pressed bar frame

(OpenDataBase Connectivity) technique. One of the results acquired at the rate of 100 S/s when a train passing by on 5th December 2003 is illustrated in Figure 9, in which vertical coordinates indicate the strains and lateral coordinates indicate the sampling points.

The values obtained from the eight sensors accord with expectation and show the reliability of the fiber optic instruments used in the system. When the train passes the monitoring spot exactly, the strain value goes up to maximum gradually. With the department of the train the value goes down to static value again gently. The maximum value reflects the load of the train.

6. Conclusions

This work studied the long-term strain monitoring of the railway bridge based on Fraby-Perot optical fiber technology. The real-time data gotten form the spot illuminates that the system has several advantages over conventional structural instruments including fast response, ability of both static and dynamic monitoring, absolute measurement, immunity to interferences such as lightning strikes, electromagnetic noise and radio frequency, low attenuation of light signals in long fiber optic cables. Results show that the system realizes the long-term and automatic monitoring timely. Namely, the Fraby-Perot optical fiber sensors can accurately measure strain and they are suitable for the long-term and automatic monitoring.

From the moment of the system was installed in the monitoring field, the strain is continuously monitored by the FP-FOS and the volume of history strain data is stored in the given database. Once the system is interfaced with the bridge expert system, it can evaluate the health state of structure online and give an alarm in case of special climate, special load or serious abnormal operation. As a result, it can avoid the calamity occurring effectually and minimize the cost of reparation and maintenance.

The work can be referenced in fields like geotechnical monitoring activities of safety and performance of earthworks and monitoring activities of major structures, such as tunnel, concrete bridges, concrete and earth dams.

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