China Ocean Engineering, Vol.12, No.2, pp.135 – 146.
China Ocean Press, 1998. Printed in P.R. China.

The W-11-4A Platform Comprehensive Strength Monitoring System

SHEN Zhonghan[*] **LI He**[**] **XUE Yinian**[*]
CHEN Junchang[***] **and ZHAO Qiang**[****]

Abstract — A comprehensive strength monitoring system used on a fixed jacket platform is presented in this paper. The long-term monitoring of W-11-4A platform achieved. Structural responses (strain and acceleration) at selected locations, as well as associated environmental parameters, have been obtained. The emphasis of the paper is placed on the system design, and the instrumentation and operation methodology employed in the monitoring of the structural responses. The performance of the system and the characteristic results obtained during its 13-month operation are also summarized.

Key words: *monitoring techniques; comprehensive strength monitoring; structural responses; waterproof strain transducers; underwater instrumentation techniques*

1. Introduction

With the continuous development of the offshore oil industry, the operation sites have been extended from near-shore to farther and deeper open sea areas, where the platforms are exposed to severe environmental disturbances including wind, wave, current, floating ice, and seismic activities. Among others, storms are usually harmful to the safety of platforms, resulting in disastrous life and / or property losses. It is hence necessary to verify and optimize the design criteria and analysis methodology employed in current practice, so that appropriate strength requirements can be satisfied and safe operation can be guaranteed.

It has been proved that long-term comprehensive monitoring of the structural behaviors of a platform in operation is a powerful measures to attain the target. Long-term distributions of the stress and acceleration responses of the platform are the most desirable data in such a project. The corresponding environmental parameters such as wind, wave and current data during the same period are also necessary in the estimation of external loads and in the verification of approaches to structural analysis.

Since late ′60s, major oil companies have launched a nember of instrumentation projects on various platforms in service. The early inverstigation mainly involved the relationship between environmental factors and the resulting loads on the platforms (Thrasher, 1969). Recently the focus of research projects has been shifted onto the prediction of the fatigue life and comprehensive strength characteristics of the platforms, mainly by means of monitoring stress responses (Ohmart, 1970; Nataraja, 1983; Swanson, 1989; Flogeland, 1985; Inglis, 1985).

Sponsored by the Research Center for Offshore Engineering of the Chinese Academy of Sciences and the Nanhai West Oil Company, the research project ″In-situ Monitoring of the

---

[*] Professor, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, P. R. China.
[**] Senior Engineer, Institute of Mechancics, Chinese Academy of Sciences, Beijing 100080, P. R. China.
[***] Professor, South China Sea Inst. of Oceanology, Academia Sinica, Guangzhou 510301, P. R. China.
[****] Applied and Computation Analysis and Modeling Program, Louisiana Tech. University,
PO Box 3827, LA 71272, USA.

Structural Strength of a Full-scale Jacket Platform″, was launched in 1991. The systematic research project was the first of its kind in China in which a long-term on-site monitoring of the comprehensive strength of a fixed offshore structure was conducted. As the object of the monitoring project, the W-11-4 production and utility platform (W-11-4A), is an 8-legged jacket platform with 8 skirt-piles, located in the Beibu Bay, the South China Sea. The platform has three major structural components: a jacket, three decks (accommodating the production and utility quarters) and living quarters. The average water depth is 40.8 m. The extreme environmental parameters (with a return period of 100 years) used in the design are: strom wind velocity, 59 m / s; wave height, 15.5m; and current velocity, 1.07 ~ 1.83 m / s.

The structural response instrumentation aspect of the project includes the following two topics. The first one is to monitor stress responses at selected tubular joints, so as to provide long-term statistics of dynamic stresses. The second one is to monitor acceleration responses at selected locations on the platform structure, so as to provide the overall structural dynamic behavior of the platform. During 13-month operation, the monitoring system accomplished the following research objectives:

1) By means of comparison of the observed structural response data and the computational results obtained from design and analysis, a clearer and deeper insight of the strength and dynamic characteristics of the platform structure was achieved.

2) By means of comparison of the observed response data and the computational results based on the observed environmental parameters, the objective of verifying and optimizing the methodology and computer programs used in practical design phase was attained. This is considered to be helpful for the design of platforms of the same kind, and for the improvement of the design level in general as well.

3) The long-term stress statistics provided a credible data base for fatigue design in the future.

In addition, the associated environmental observations are also helpful in future design practices.

2. Platform Structure Response Monitoring System

The structure response monitoring system is the kernel part of the project. It is extremely important to come up with a rational design which could meet all the technical requirements. The remarkable aspects are as follows.

2.1 Stress Measurement

As described in the previous section, the importance of stress measurement lies in that it provides raw data for the analysis of joint stresses and fatigue behaviors. Therefore it is the basis to investigate the realistic comprehensive strength characteristics of the platform structure, and hence the basis to verify and improve design techniques.

This is achieved by measuring strain responses at selected locations and then converting strain values to the corresponding stress values. The plan for locating measuring sites is determined by the following procedure:

2.1.1 *Determination of the Measuring Sites Based on Finite Element Analysis (FEA) Results*

The tubular joints where the branch pipes were subjected to high stresses were selected, as strain monitoring sites. These joints were vulnerable to significant fatigue damage as well. The platform structure was modeled by using an Offshore Platform Analysis Package (OPACK) developed by the Institute of Mechancics, Chinese Academy of Sciences, and suitable monitoring sites were determined by the results of finite element analysis from the quasi-static and dynamic runs. In the process, results from the quasi-static and fatigue analyses conducted in the design phase (Bohai, 1991) were also refered to.

2.1.2 *Selection of Planar Joints*

Only the planar joints which met the previous requirements were selected for the comparison of the observed and predicted results. The four selected monitoring areas (A, B, C and D) were located on Row-4, Row-A, and the planar frame at level −9.6 m, as illustrated in Fig.1.

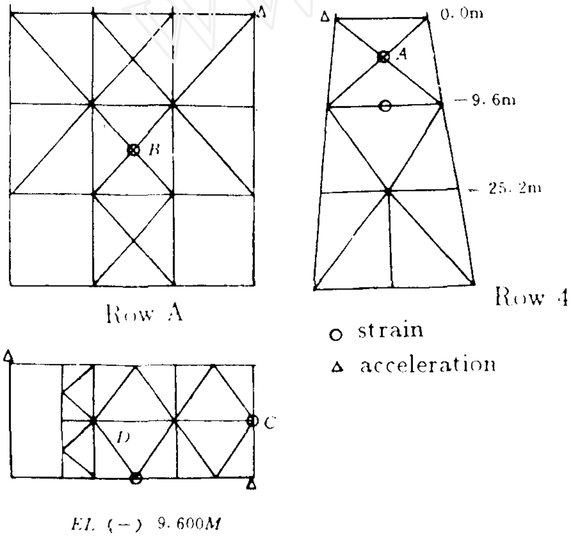

Fig. 1. Locations of strain monitoring areas and acceleration tranducers.

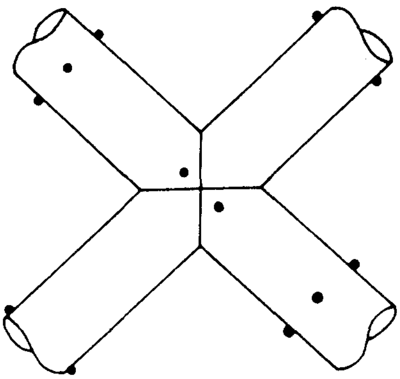

Fig. 2. Site plan of strain monitoring area A.

2.1.3 *Keeping Away from Drilling and Operation Areas*

All the monitoring areas selected were away from drilling and operation areas. This was proved to be very convenient during both installation and operation. The undesirable disturbances from engineering equipment could be isolated from monitoring signals.

2.1.4 *Waterproof Protection Pipeline System*

As shown in Fig. 2, the strain gauges in each area were located along branch pipes crossing at the selected joints. There were 12 to 16 sites for gauges in each area. Each site was protected by a specially designed waterproof apparatus, with a waterproof hose connected to a concentrator mounted near the center of the monitoring area. Steel pipelines were used to provide protection for the signal cables, which connected the concentrators to a storage cabin at the level 6 m above the sea surface. The storage cabin was used as a hub of the protection system.

2.1.5 *Plans for Strain Guage Allocation*

There were three different allocation plans for strain gauges at each site, namely, (a) one or (b) two normal gauges, and (c) one rosette. A single normal gauge was used to measure the axial stress, whereas a rosette could determine both the direction and the magnitude of stress. The double-gauge plan was intended to extrapolate the hot-point stress, the stress value at the weld toe. Each double-gauge site was located right off a weld toe of interest, with the two gauges laid in a line perpendicular to the weld.

The measuring sites in each area were illustrated in Figs. 3 and 4. There were 16 sites in areas A and B, 15 in area C, and 12 in area D.

2.2 Acceleration Measurement

Five locations were selected for installation of acceleration transducers. One was located on leg A-4, 6 m above water. The rest were located at each of the diagonal corners of the top two decks, 24.6 m and 32.6 m above the sea level, respectively. In other words, the acceleration transducers were along legs A-4 and B-1, as illustrated in Fig. 5. At each point, the movements along x and y directions were measured, x and y being in the long and short axes of the platform plane, respectively. A waterproof protection apparatus and a set of installation procedures were carefully designed, in order to protected the transducers from mechanical damage, and the humid and corrosive environment.

2.3 Design and Installation of Signal Cables

Several problems were taken into consideration in making plans concerning signal cables. The distances from the strain gauges to the control cell ranged from 50 m to 80 m. Some signals as weak as just several microvolts had to be conducted over the spans. Tough restrictions also arose from the balance of the strain measuring bridge, where the tolerance for resistance variation was no more than 0.5 ohm. Threrefore the cable to be used should possesss an excellent electrical conductivity. And each cable was assumed to be one single piece throughout its span without any knot, so as to keep a small resistance value. In addition, the cable should possess good water-resistant quality, because about one quarter of the cable length was laid under the sea surface. To this end, protection measures with unique features were taken to prevent the cables from the sea water.

The part of the cables located below and near the sea level was protected by waterproof pipelines. From each gauge to the concentrator which is in the corresponding monitoring area, a composite rubber hose of an inner diameter of 8 mm was used. These hoses were of high strength and were tough to sea water corrosion. From each concentrator to the storage cabin, steel pipes of an inner diameter of 60 mm were used. The cables were connected to every gauge when the jacket was constructed onshore. The part of cables leading to the control cell, which

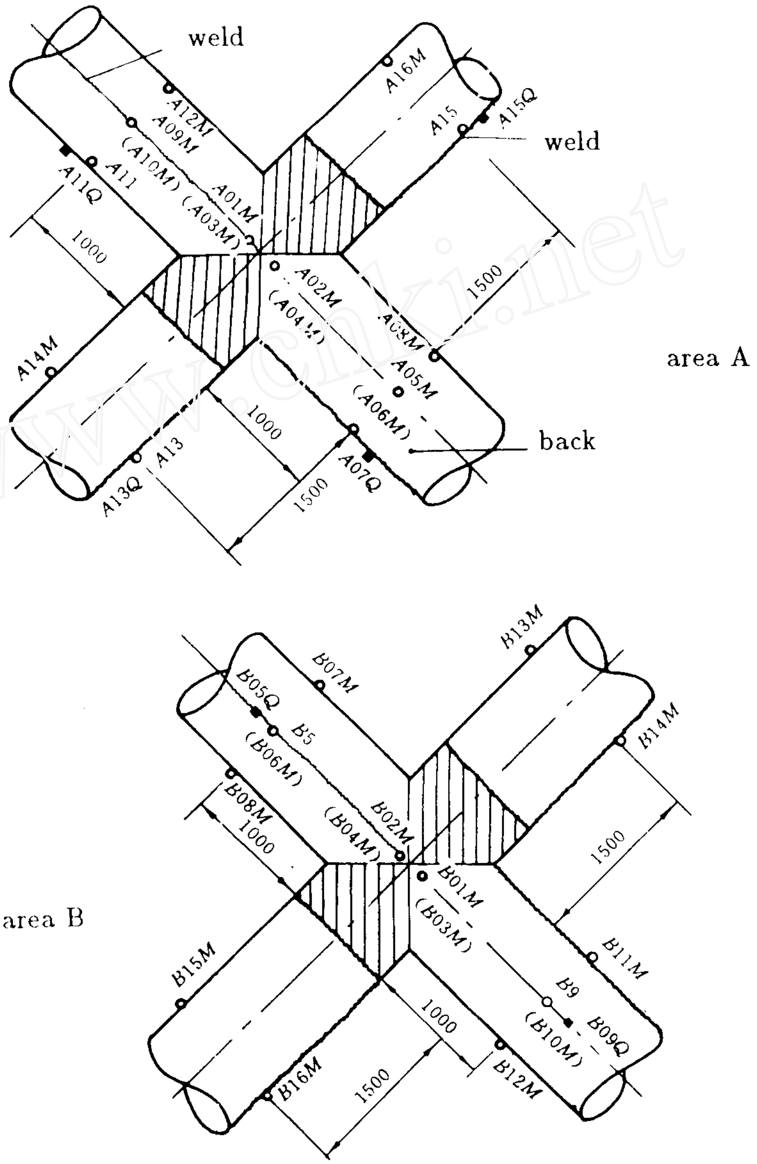

Fig. 3. Site plans of strain monitoring areas A and B.

中国海洋工程(98,第一期 外文版)

was located in the living quarters on the top deck, was stored in the cabin before being installed offshore. The cabin was then sealed, until the super structure of the platform was successfully mounted. After that, the cables were pulled out of the cabin, and connected to the control cell.

U- section steels were used, covering the cable bundle and being welded to vertical

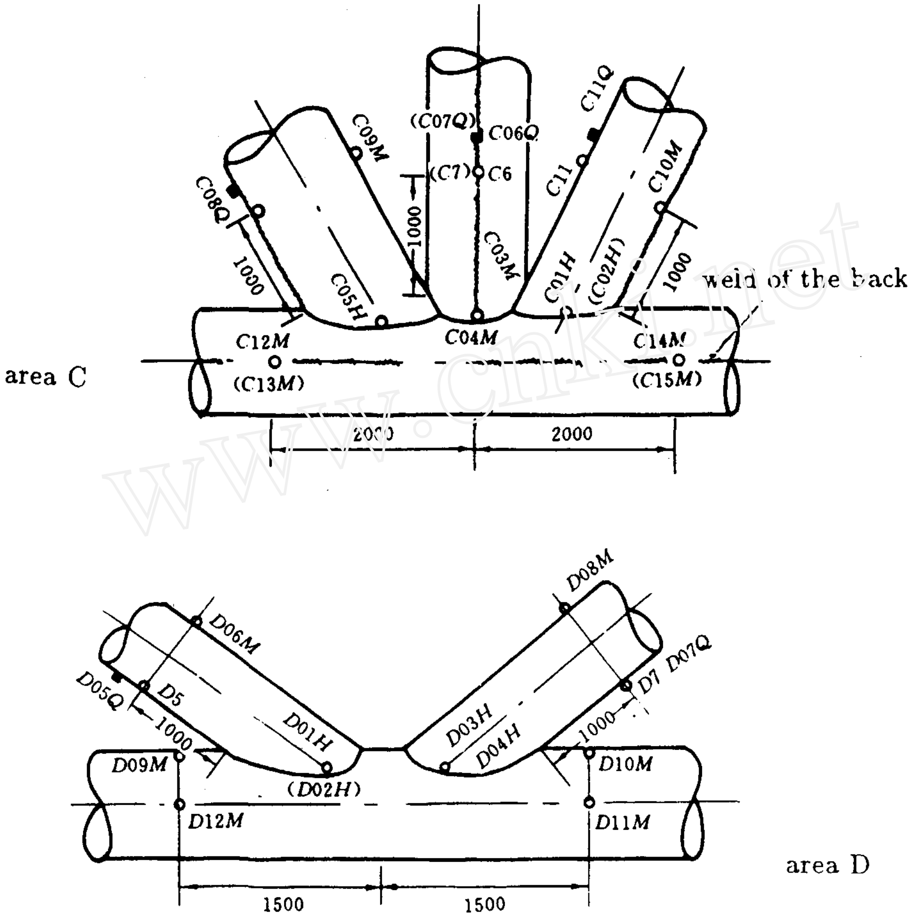

Fig. 4. Site plans of strain monitoring areas C and D.

pipes, to provide mechanical protection. The outlet of the storage cabin was sealed with an effective adhesive to protect it from wave splashes and rain.

Cables connecting the accleration transducers were protected in a similar way.

2.4 Sensing Elements and Measuring Equipment

The strain sensing elements were wire resistance strain gauges (3 mm × 5 mm), with a resistance of 120 ohm and a sensitivity of 2.0. The half bridge circuit was used. A working gauge was mounted on the structrual element at a selected site. The compensation gauge was glued to a dummy made of the same type of steel as that of branch pipes, and was fixed within the same waterproof cover. The output signal was transited to one of the 24 YF-3 amplifiers. The bridge voltage was set at 5V, and the resulting sensitivity was 12.5 mV per microstrain. There were five options for the truncation frequency of the built-in low-pass filter in the amplifiers, 10 Hz,

《中国海洋工程'98第二期 外文版》

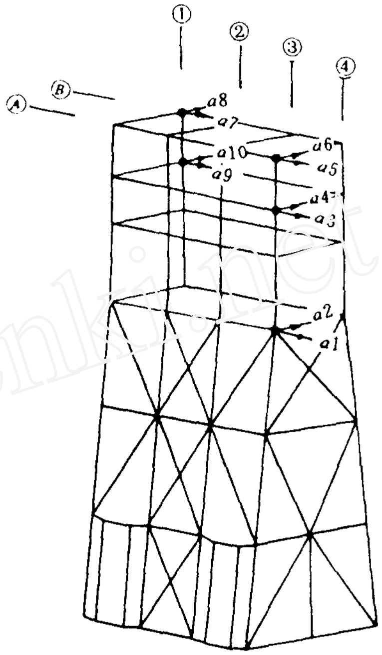

Fig. 5. Sketch for the acceleration tranducer allocation design.

100 Hz, 1 kHz, 10 kHz, and all-pass. The 10 Hz option was used, since the signal of interest was induced by wave loads, whose frequency usually ranged below 1 Hz.

The acceleration transducers used in the system were WLJ- 200 force equilibrium acceleration transducers, which had excellent performance in the low-frequency range. The sensibility of the transducers was up to 1000 V / g, i. e., the output voltage was 100 V when the acceleration was 1 m / s^2. Filters were added at the output ends, in order to remove the high-frequency disturbance and to improve the signal-noise ratio. The major equipment was certificated by the China Institution for Measurement and Instrumentation Sciences before used in the system.

Automatic data acquisition equipment was designed to process voltages within the range of −5 V to + 5V. Therefore, each accleration output was reduced before the A / D conversion to avoid the clipping phenomenon.

There were totally 58 individual signal channels in the strain and acceleration monitoring system, of which 48 were strain channels, and 10 were acceleration channels.

2.5 Environmental Parameter Measurement

A single-channel OMC anemometer was installed on the top of the platform, which was used to record the velocity (instantaneous or averaged) and direction of the wind. A CBS wave gauge was installed off Row-B of the platform to monitor the fluctuation of the wave height.

Aanderaa current-meters were also installed to measure the current velocity at various heights below the sea surface.

The overall plan of the monitoring system is sketched in Fig. 6.

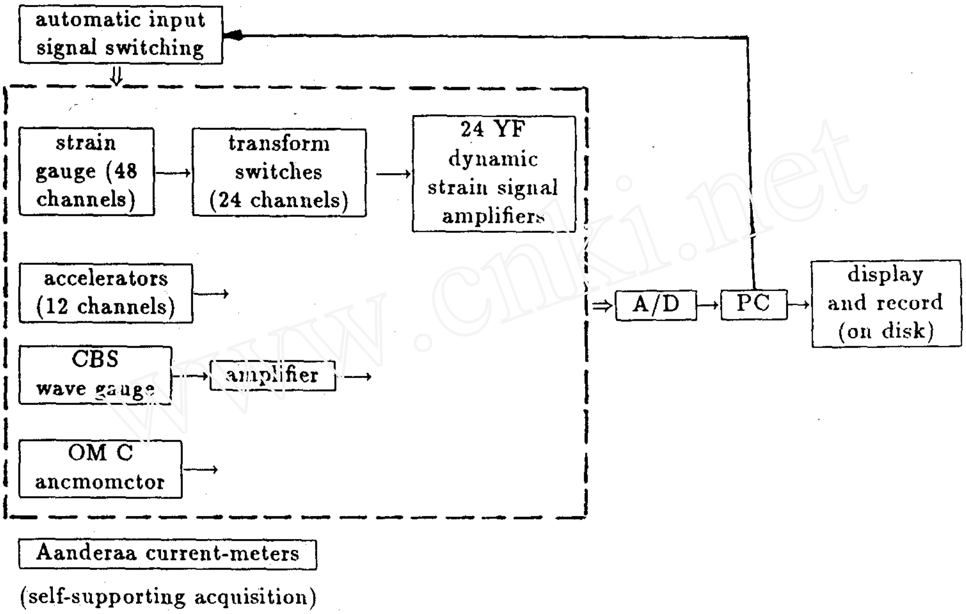

Fig. 6. *Sketch for the monitoring system configuration.*

3. System Development and Operation

With the nature of both scientific research and engineering technology, the development and operation process of the W-11-4 monitoring system can be divided into three phases, namely, prototype study and design, installation, and testing and operation. The major features of each phase are described below.

3.1 Prototype and Design

Because the whole system was to be submerged or exposed to a highly humid and corrosive environment, the essential requirement for the system must be waterproof. The protection apparatus should be able to survive the long-term high pressure submarine condition. The insulation between the strain gauge and the tested structure was critical to the accuracy of sampling data. It could be damaged by even the slight moisture under the waterproof cover. In order to come up with the appropriate techniques which met the stringent requirements, numerous lab tests had been conducted to verify the performance of each device and material under specified conditions. These tests include:

(1) Verifying watertightness of the strain gauge cover under high pressure

The long- term performance of the specially developed waterproof apparatus was verified under a pressure much higher than the practical operation condition. With a series of tests and improvements, the suitable apparatus was finally developed.

(2) Testing the performance of sealing adhesives

The waterproof and mechanical performance of various adhesives were tested so that the suitable one was chosen and the appropriate curing techniques were determined.

(3) Testing the effects of the protection apparatus on the mechanical behavior of the structural elements to be measured.

(4) Testing the effects of adhesives on the gauge readings.

(5)Testing the anti-disturbance performance of the selected cable conducting weak signals through a long distance.

It was proved that the effects of the protection apparatus on the gauge readings were negligible and would not influence the accuracy of measurement.

3.2 Equipment Installation

The next phase was system installation. The tasks included the mounting of strain gauges at all the selected positions in areas A, B, C and D; the installation of protection apparatus; and the connecting of cables from the sensing elements distributed over various monitoring areas to the storage cabin. The 60 cables, with a total length of 6000 meters were drawn through the protection pipelines. That was a tedious job which needed extreme patience.

The technical requirement for the installation of the acceleration transducers was mounting them as close as possible to the platfrom frame onto which they were attached. This was because the rigid connection between the transducer and the structure was very important in the monitoring of the actual motion of the platform by eliminating or reducing the disturbances resulting from drilling and processing operations.

The major task of on-site installation was to mount the acceleration transducers properly. As mentioned previously, they were designed to be mounted on a horizontal basis, and laid along the two axes of the platform plane. Proper covering of the transducers with the protection apparatus was also very important.

3.3 Debugging and Operation of the Monitor System

After the entire equipment was installed, the system was integrated and tested. The automatic channel switching and data digitization and acquisition functions were also verified. The system was equipped with an unintermitent power source (UPS), which could guarantee the quality of voltage output to the system all the time and enable automatic operation during storms.

4. Typical Observations and Result Analysis

A series of valuable observations were achieved during the 382-day operation of the monitoring system. These results helped to reveal the long-term strain statistics, and the relationship between the strain signals and the environmental conditions, including the wind, wave and current.

4.1 Strain Measurement Results and Analysis

Transient strain curves fluctuated with periods ranging from 3 to 7 seconds, and peak values from 30 to 60 microstrains. This was coincident with the wave periods, and verified the commonly accepted knowledge that the wave is usually the dominant source of exterinal loads acting on the platform. Statistic analyses showed a good relationship between the maximum strain value and the observed wind speed, which was the best recorded environment data. Fig. 7 shows the relation for over 40 consecutive days. The co-relation factor ranged from 0.54 to 0.96. This can be understood when the fact is noticed that powerful waves are usually generated by a strong wind process which lasts in a certain direction for a period of time.

The power spectrum analysis of strain signals showed that the noticeable spectra were all clustered in the low frequency range (below 1 Hz). Fig. 8 gives an example, in which the peak frequency is about 0.15 Hz, coincident with the observed wave period of about 7.0 seconds. This means the structural dynamic amplification phenomenon was negligible.

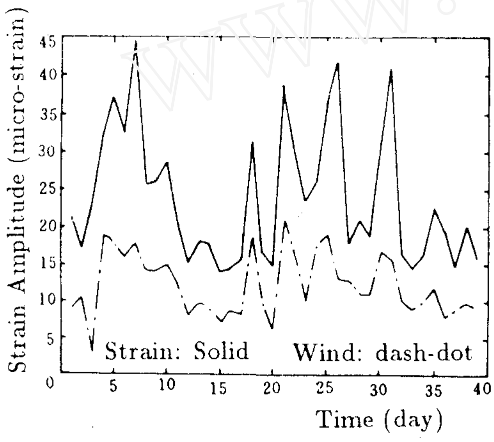

Fig. 7. The maximum strain variation for 40 consecutive days.

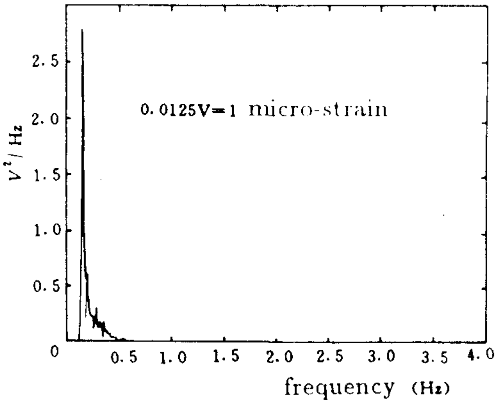

Fig. 8. A typical power spectrum curve for the strain sample.

An exception was given by the observations under the condition of an accidental crash of a service vessel to the platform. In that case, peak amplitudes of over 100 microstrains were recorded, and soon reduced to the magnitudes prior to the crash. The peak frequency transited to about 1 Hz, which was the fundamental natural frequency of the platform.

4.2 Typical Acceleration Measurement Results

Fig. 9 shows a typical power spectrum curve of an acceleration sample observed under the natural environmental condition at transducer as (Fig. 5), which was laid along y-axis or the short axis of the platform plane. The two significant spectra show two of the natural frequencies of the platform structure, 1.00 Hz and 1.37 Hz.

Spectrum analysis results revealed that the natural frequencies associated with the 1st

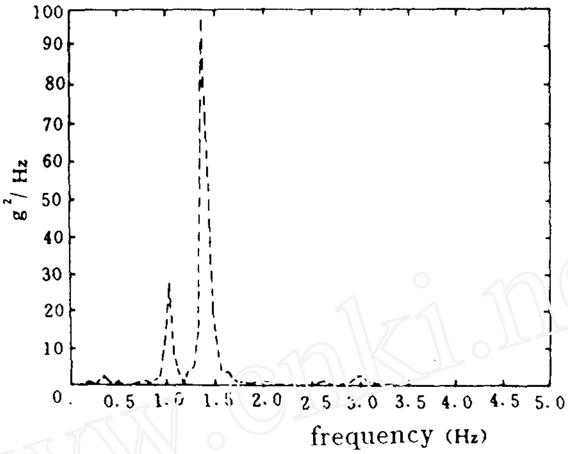

Fig. 9. A typical power spectrum curve for the acceleration sample.

bending mode along x and y(or long and short) axes, and the 1st rotation mode in the $x-y$ plane were 0.97 Hz, 1.00 Hz and 1.37 Hz, respectively. The modal damping coefficient associated with the 1st x bending mode was 0.016, which was determined by analysis of the data recorded during the crash mentioned above.

5. Conclusions

From December 1993 to the end of December 1994, the W-11-4A monitoring system successfully operated 382 consecutive days, a great number of first-hand data were observed. All the planned targets have been fulfilled. The following conclusions can be drawn.

(1) The stress and acceleration monitoring system operated successfully, and the measuring site allocation plan was proved to be rational. These laid a solid foundation for attaining all the proposed research targets.

(2) The operation of the system proved that both the instrumentation system and the protecion system were rationally designed and their performance was good. After its installation, the strain monitoring system was submerged together with the jacket for over a year. During that period, the system underwent a series of engineering processes, including launching, drawing, and piling. Out of the 83 strain channels installed onshore, 50 or 60% of them gave reliable signals when the system was integrated in November 1993. The survival rate was satisfactory. Most of the lost channels were located in area D, to which unexpectedly severe crashes might have happened during the transporting and piling processes, because deficiencies of mounting and sealing techniques should have led to losses which were uniformly distributed over all the four areas.

(3) Among the 50 strain channels which survived when the system started to operate, 48 or 96% of them worked well till the end of December 1994 and could still work longer. This means that the system had survived in the submarine environment (up to 20 m below the sea) for

almost two years since the jacket was first floated. This was rarely reported in similar instrumentation projects.

(4) The lower bound of the frequency window of the acceleration monitoring system was as low as 0.1 Hz. This guaranteed the accurate measurement of the response to the wave and current action, which was of very low frequencies.

References

Bohai Engineering and Design Corporation, 1991. Report for Detailed Design. (in Chinese)

Flogeland, S., 1985. A systematic Development of Sevices for Instrumented Structural Monitoring, *OTC*, **5042**, 195~206.

Inglis, R. B. and T. E. Knit, 1985. Predicted and Measured Lonc Term Stress Rance Distributions for the Fulmat a Platform, *Behaviour of offshore Structures*, 153~165.

Nataraja, R., 1983. Structrual Integrity Monitoring in Real Sea, *OTC*, 4538, 221~228.

Ohmart, R. D., R. L. Gratz and G. O. Mallery, 1970. Instrumentation Program for Evaluation of Offshore Structure Design, *OTC*, **1264**, 391~396.

Swanson, R. C., 1989. The Bullwinkle Platform Instrumentation System, *OTC*, **6052**, 93~100.

Thrasher, L. W. and P. M. Aagaard, 1969. Measured Wave Data on Offshore Platfroms, *OTC*, **1007**, 83~94.