Dynamic deformation monitoring of an offshore platform structure with accelerometers

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Abstract

In this paper, structural characteristics are evaluated by displacement and frequency indicators that indicate the real-time health status of offshore platforms. This paper uses an accelerometer to collect the dynamic response of the platform in the event of a ship collision. The main contributions of this research are reflected in three aspects. Firstly, based on Empirical Mode Decomposition (EMD) multiscale decomposition, the noise range is determined according to the scale and the average value of the standardized accumulation mode, and the original acceleration sequence is denoised. Secondly, two impact tests were carried out to understand the platform's structural characteristics under an external load. Combined with the FFT algorithm and Hilbert Huang transform, the three-dimensional information of the time, frequency, and energy is analyzed. Finally, a method of high-frequency dynamic displacement reconstruction is proposed. According to the extracted vibration frequency information, the parameters for the filter are reasonably set, and the denoised acceleration time sequence is processed with bandpass filtering and quadratic integration to obtain the high-frequency dynamic displacement of the structure. The results show that the high-frequency dynamic displacement of the accelerometer reconstruction is 1.5 mm. Two collision event frequencies, 1.477 Hz and 1.483 Hz, were successfully extracted from the north direction.

Keywords Offshore platform · Structural health monitoring · Accelerometer · Frequencies extraction

1 Introduction

In recent decades, with the rapid development of oil exploitation, offshore platforms have been widely used. However, the environment around the offshore platform is complex and affected by wind, wave and current over long periods. Therefore, it is necessary to consider the impacts of disastrous environmental forces such as typhoons, ice or earthquakes, as well as accidents such as ship collisions, on the

health and safety of offshore platforms and how these events may affect the long-term safe operation of such structures. During long-term service, the accumulation of damage from stress and strain caused by multiple events can seriously threaten the regular use of the structure. There is an urgent need to establish a more complete monitoring system that uses appropriate monitoring measurements to accurately evaluate the health status of offshore platforms in real-time. To understand the structural characteristics under different loads, it is essential to measure displacement and frequency to understand the dynamic response of the structure, which in turn, are necessary for the safety evaluation.

The integrity of structures can be evaluated by measuring displacement. The Global Navigation Satellite System (GNSS) positioning technology has many unique advantages compared with other traditional monitoring methods [1]. Xiong et al. [2] used GNSS RTK dual-frequency receiver to monitor the dynamic deformation of offshore platform legs. A new hybrid filter combining Ensemble Empirical Mode Decomposition (EEMD) and the Butterworth filter was proposed to effectively remove the GNSS signal's multipath effect and random noise. This allows the dynamic response

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of the platform under environmental load to be obtained to the required level of accuracy. However, there are only a few investigations that study the deformation monitoring of offshore platforms using GNSS. GNSS has, however, been widely used as a technique for monitoring similar large structures.

For example, Roberts et al. [3, 4] analyzed the deflection change of bridges under traffic load and compared it with the finite element model. The magnitude of quasi-static deflection and the frequency of structural dynamic response was acquired. The filtered signal is transformed into the frequency domain using FFT analysis, and the primary frequency and amplitude of the structure are obtained. Discrete Wavelet Transform (DWT) and Fourier transform (FT) can also be utilized to analyze the observation data for the movement of bridge towers under different stresses [5]. The dynamic characteristics of bridges can also be evaluated using the time series of wavelet spectrum analysis [6]. In an ideal observation environment where RTK GNSS positioning is used to monitor deformation, the accuracy can reach millimeter level. Even ionospheric and tropospheric errors are eliminated using differential processing. However, the measurement results are still affected by the multipath effect and measurement noise [7]. This can be somewhat overcome by using multi-GNSS techniques to process the data and choose the best set of satellites to obtain the optimum solution [8]. GNSS using precise point positioning (PPP) algorithms has also been used for structural monitoring techniques and may also be an appropriate technique for the monitoring of offshore platforms. Due to the lack of base station data close by for differential GNSS, recent research has shown the potential for using PPP for these applications. However, the accuracy is still lower than differential GNSS [9]. In the special environment of the ocean, the refractive index of the sea surface increases, and the multipath effect is significant. In addition, the long-baseline length can increase the difficulty of obtaining the required accuracy using GNSS for this application.

Many sensors can monitor the static, quasi-static and dynamic deformation of structures, and accelerometer sensors are widely used in structural health monitoring [10]. The accelerometer has a sampling frequency of up to 1000 Hz, which is used to identify the dynamic parameters of structures [11]. When the acceleration information of the object is obtained, the velocity and displacement information of the object is calculated using integration [12, 13]. However, due to the zero-bias of the accelerometer, with the increase of integration times, the phenomenon of "drift" will appear [14], making it difficult to accurately measure the static and quasi-static displacement. The error will become relatively large through continuous integration, and the integral velocity and displacement signals will be significantly distorted. Velde et al. [15] studied

two correction methods, reducing the error of indirectly obtaining displacement from acceleration records. Vaccaro et al. [16] proposed a method to estimate the structural displacement using accelerometers and verified the algorithm's performance by collecting and analyzing the measured data from a bridge. Due to the difficulty of establishing a fixed reference point, it is difficult to monitor the long-term displacement of civil engineering structures. The numerical integration of the acceleration signal is a common low-cost displacement measurement method. An online real-time acceleration integration scheme is proposed in [17]. The applicability of the scheme has been verified by utilizing the proposed system on a real bridge. Digital Signal Processing (DSP) integration algorithm removes the interference noise and trend term in the vibration acceleration signal. The integration result becomes closer to the real signal [18].

To date, offshore platforms' real-time health monitoring system is still not mature. The monitoring data is inevitably mixed with noise, which is not conducive to identifying vibration information, especially in real-time. This paper introduces field tests conducted on the CB246A offshore platform in Shengli Oilfield of Dongying to measure the displacements at the platform top caused by collisions with ships. By analyzing the dynamic response of offshore platforms, it is evident that there is a significant correlation between external load and platform vibration. To promptly monitor the offshore platform's health status, the dynamic response of the structure during two-ship collision events is obtained using an accelerometer. The data collected using the accelerometer during these events are used to validate the proposed method. The original acceleration sequence is denoised by using a bandpass filter, and the vibration frequencies are extracted. At the same time, the high-frequency dynamic displacement of the structure is calculated using acceleration. The main contributions of this research are as follows. Firstly, a scheme of reconstructing dynamic displacement using acceleration is proposed. This scheme can obtain dynamic displacement and form a reliable basis for offshore platform structure health monitoring. This work's second contribution is the use of HHT and FFT to reliably extract the frequencies of two impact events.

This paper is organized as follows. In Sect. 2, the theoretical model and technical route of the method are described in detail. In Sect. 3, the feasibility of the algorithm is verified by the vibration simulation platform test. In Sect. 4, the current situation of the platform and the experimental scheme are introduced. In Sect. 5, two collision experiments are analyzed. The frequencies are extracted, and the dynamic displacement is constructed more accurately, which verifies the method's applicability. Section 6 summarizes the technical methods of this paper and gives the relevant conclusions.

2 Methodology

The vibration signals of structures under environmental excitation are mostly nonlinear and non-stationary. For the structural health monitoring of an offshore platform, the external excitation, such as wind, wave and currents, is more complex in nature. Therefore, the traditional time-domain and frequency-domain analysis methods have some limitations to the application of monitoring offshore platforms. A Fourier transform is a kind of global transform, which lacks local information and decomposes the signal into different frequency components. A Wavelet function contains a series of basic functions, which can be used to analyze local signals in both frequency and time domains and provide a multi-resolution analysis of non-stationary signals. The Hilbert-Huang (HHT) transform is also suitable for processing non-stationary signals, especially for identifying time-varying system modal parameters [19]. In this paper, to make up for the lack of local information in FFT, HHT is selected to identify the structural characteristics of the platform under complex ambient loadings and obtain more comprehensive three-dimensional information of the time, frequency and energy.

HHT comprises the Empirical Mode Decomposition (EMD) and the Hilbert Spectral Analysis (HSA). HHT aims to obtain the instantaneous frequency and amplitude with practical physical significance in the signal and then realize high-resolution time–frequency analysis.

2.1 Hilbert-Huang transform

2.1.1 Empirical mode decomposition

As an adaptive time–frequency processing method for nonlinear and non-stationary signal analysis, EMD was proposed by Huang et al. [20] at NASA in 1998. According to time scale characteristics of the data, the original signal is filtered repeatedly to obtain the Intrinsic Mode Function (IMF). The lowest frequency IMF component obtained by EMD usually represents the trend or mean value of the original signal. In this sense, this method can effectively extract the trend of a signal or remove the mean value of the signal.

EMD is mainly divided into three stages, and the specific steps are as follows:

1. The maximum and minimum values of signal $x(t)$ are found, and the upper and lower envelope lines are obtained by cubic spline fitting. At the same time, the mean value $m_1(t)$ is obtained.
2. The first component $h_1(t) = x(t) - m_1(t)$ is obtained, and check whether the following modal component conditions are satisfied:
 - a) The difference between the maximum value of $h_1(t)$ and the number of zero-crossing points is up to one.
 - b) The average value of the upper and lower envelope of $h_1(t)$ is zero.

If the condition is not met, repeat operations 1 and 2 until the mode component $imf_1(t)$ satisfying the IMF condition is obtained.
3. The first mode component is subtracted from the original signal to get the signal $r_1(t) = x(t) - imf_1(t)$, and $r_1(t)$ is called a new "original signal". Repeat the above operations until $r_n(t)$ is basically monotonous or $r_n(t)$ is very small, which can be regarded as a measurement error.

In this way, the original signal is decomposed into a finite number of empirical mode components and a residual signal:

$$x(t) = \sum_{i=1}^n imf_i(t) + r_n(t) \quad (1)$$

2.1.2 EMD noise reduction

The EMD method can decompose the signal adaptively according to its own characteristics, but modal aliasing is inevitable. When the signal has a slowly changing trend, the scale and the mean of standardized accumulated modes are defined as follows [21]:

$$\hat{h}_m = \text{mean}(\sum_{i=1}^m (imf_i(t) - \text{mean}(imf_i(t))/\text{std}(imf_i(t)))) \quad m \leq n \quad (2)$$

where $imf_i(t)$ is the modulus of the i -th scale. If $\hat{h}_m$ deviates from zero, it is considered to be caused by the trend change of the system from scale m . The trend items extracted from the signal are:

$$\hat{x}(t) = \sum_{i=m}^n imf_i(t) + r_n(t) \quad (3)$$

where $imf_i(t)$ is the i -th scale IMF signal, $r_n(t)$ is the residual signal.

In this paper, the IMF component, which obtains the local minimum for the first time, is taken as the standard. The former component is removed as the high-frequency noise. The residual component and residual term are reconstructed to obtain the denoised acceleration sequence.

2.1.3 Hilbert transformation

After the EMD decomposition of a signal $x(t)$, the finite intrinsic mode component IMF $c_i(t)$ is acquired, by

calculating the convolution of $c_i(t)$ and $1/\pi t$, the Hilbert transform $H[c_i(t)]$ can be expressed as:

$$\hat{c}_i(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{c_i(\tau)}{t - \tau} d\tau \quad (4)$$

The instantaneous frequency and amplitude of the corresponding IMF are given by (6):

$$f(t) = \frac{\omega_i(t)}{2\pi} = \frac{1}{2\pi} \frac{d\theta_i(t)}{dt} \quad (5)$$

where $\theta_i(t)$ is the instantaneous phase, $\theta_i(t) = \arctan(\hat{c}_i(t)/c_i(t))$

Then the original signal can be expressed as:

$$x(t) = \sum_{i=1}^n a_i(t) e^{j \int \omega_i(t) dt} \quad (6)$$

where $a_i(t)$ is the instantaneous amplitude and $\omega_i(t)$ is the instantaneous angular frequency. After n times of the EMD decomposition, the residual signal $r_n(t)$ is a constant or monotonic function, which has no substantial effect on signal extraction, so it can be omitted.

The marginal spectrum can be obtained according to the solution formula as follows:

$$h(\omega) = \int_0^T H(\omega, t) dt \quad (7)$$

where t is the period, this formula is fixed ω invariant for t integral. The definite integral can be approximately decomposed into the area sum of several rectangles in the discretization. In the discrete signal, $H(\omega, t)$ is the time spectrum matrix $H(\omega, k)$, the length of the rectangle is $H(\omega, k)$ corresponding to the k -th data, and the width is the time interval, that is, $\Delta t = 1/f_s$ (reciprocal of sampling frequency), so the integral formula can be rewritten as:

$$h(\omega) = \sum_{k=1}^N H(\omega, k) * 1/f_s \quad (8)$$

In the time domain, Hilbert energy can be obtained by integrating the square of $H(\omega, t)$ with time. This represents the energy accumulation $ES(\omega)$ of each frequency over the whole length of time. The expression is:

$$ES(\omega) = \int_0^T H^2(\omega, t) dt \quad (9)$$

In the frequency domain, the Hilbert instantaneous energy spectrum can be obtained by integrating the square of $H(\omega, t)$ with the frequency:

$$IE(t) = \int_{\omega_2}^{\omega_1} H^2(\omega, t) d\omega \quad (10)$$

Instantaneous energy $IE(t)$ represents the energy accumulated in the whole frequency domain at each time.

2.2 Dynamic deformation reconstruction

The accelerometer has a high sampling frequency (up to 1000 Hz) and consequently is sensitive to high-frequency information. This high-frequency data allows the dynamic response of the structure, which is high frequency, to be obtained. The noise in the acceleration data is removed by using a bandpass filter. Then the displacement is calculate using a double integral equation, as follows, although the initial value is difficult to determine:

$$s(t) = s_0 + v_0 \times t + \int_0^t \left(\int_0^t a(t) dt \right) dt \quad (11)$$

where $s(t)$ is the displacement of time t , $a(t)$ is the acceleration of time t , s_0 is the initial position and v_0 is the initial velocity.

Initial position s_0 and initial velocity v_0 cannot be measured by an accelerometer, and they must be calculated by other methods. This initial value problem can be solved by using accelerometers to obtain only the dynamic displacement, taking a specific value as the initial position value to calculate the relative displacement, and adjusting according to the static or quasi-static displacement measured by GNSS [22].

2.3 Spectral analysis of a dynamic deformation

In practical applications, the FFT algorithm is used to estimate the power spectral density. FFT is a Discrete Fourier Transform (DFT) algorithm based on the transformation of discrete measured values from the time domain to the frequency domain. In mathematics, the N -point DFT of a complex input $x(n)$ [23] can be defined as:

$$Y(k) = \sum_{n=0}^{N-1} x(n) W_N^{nk} \quad (12)$$

where $k \in [0, n-1]$ is the index of the output sequence $Y(k)$.

The rotation factor W_N^{nk} is defined as:

$$W_N^{nk} = \exp(-2j\pi nk) \quad (13)$$

The arithmetic operation of DFT is too complicated to be used effectively in practice. The appearance of FFT can reduce the computational complexity of the DFT. In this paper, the FFT algorithm is used to analyze the frequency spectrum and obtain the dynamic response of the structure.

2.4 Data processing analysis

In this research, the accelerometer is used to obtain the structural dynamic response of offshore platforms in two different scenarios: collision frequency analysis and dynamic displacement reconstruction. The flow chart is shown in Fig. 1, and details are as follows:

Firstly, the original accelerometer data is decomposed by EMD based on standardized cumulative modulus, and the useful signal and random noise are separated to obtain the denoised acceleration sequence. Furthermore, the FFT algorithm and peak-picking approach were used to extract the frequency response and primary amplitude. The HHT method is used to analyze the time, frequency, and energy of vibration events in detail to capture more information.

Secondly, after the acceleration de-noising sequence was processed using the bandpass filter, quadratic integration and linear trend removal were performed to obtain dynamic high-frequency displacement. The extracted vibration frequency and high-frequency dynamic displacement are used as monitoring indexes to provide a basis for structural health evaluation.

3 Vibration simulation platform test

3.1 Introduction of a vibration platform test

A series of vibration simulation platform tests were carried out with GNSS and accelerometer to verify the reliability of the proposed model and displacement reconstruction method. The control terminal can set different vibration frequencies and amplitudes, control the vibration platform to move along the X and Y axes of the plane, and simulate deformation. The components are shown in Fig. 2. GNSS RTK mode was adopted to deploy the base station and monitoring station. Considering that the RTK positioning error increases with the increase of baseline length, the base station was set on the College of Surveying and mapping

Fig. 2 Vibration simulation platform

roof, and the monitoring station was set at the South Gate of the school. The GNSS antenna was placed on the vibration platform. The platform vibration response was collected by GNSS receiver with a sampling frequency of 5 Hz and inertial navigation accelerometer module with a sampling frequency of 100 Hz. The x-axis of the vibration platform referred to the north direction while maintaining the same direction and time synchronization between the inertial navigation system and the system to facilitate the data comparison and analysis of the two sensors.

For the three groups of simulation tests, the frequency was set at 1.5 Hz, the duration was 3 min, and the amplitudes were 10 mm, 30 mm and 50 mm, respectively. Taking the original acceleration data of x-axis as an example (Fig. 3), it can be clearly seen that three groups of regular acceleration change series with time.

Fig. 1 Overall flow chart of data analysis

Fig. 3 Original data of *x*-axis acceleration time series

Fig. 4 X-axis frequency extraction of vibration platform simulation experiment

3.2 Frequency extraction and displacement reconstruction

Three groups of analog accelerometer data were processed, and FFT was used for spectrum analysis. As shown in Fig. 4, the extracted frequency is 1.5 Hz. However, the FFT peak picking method can only obtain the global transformation. It can not obtain detailed information on the time and amplitude of the three groups of vibration experiments. In contrast, three groups of experimental results can be clearly seen in the Hilbert spectrum (Fig. 5). The frequency is 1.5 Hz, and multidimensional information such as occurrence time, duration and energy can be obtained simultaneously, indicating the advantages and applicability of this method.

Fig. 5 X-axis Hilbert spectrum of vibration platform simulation experiment

Fig. 6 Comparison of acceleration integral displacement and GNSS original displacement

Taking the vibration frequency of 1.5 Hz and amplitude of 50 mm as an example, this paper verifies the proposed displacement reconstruction algorithm. The acceleration data was processed by 1–1.6 Hz bandpass filter, and then quadratic integration was carried out. After removing the linear trend, the final integrated displacement result was compared with the original displacement sequence of GNSS, as shown in Fig. 6. It can be seen that the two displacements are basically consistent. However, the GNSS monitoring data is affected by random noise, which is slightly larger than the integral displacement of the accelerometer, which verifies the possibility of the accelerometer to obtain the structural displacement.

Fig. 7 The CB246A offshore platform

4 Field experiment

4.1 Platform introduction

The offshore platforms in China are mainly constructed in shallow water, with a design life of about 20 years, and lack dedicated safety monitoring and maintenance equipment. The CB246A offshore platform in Shengli Oilfield of Dongying was built in 2004 (see Fig. 7). The whole platform is a steel structure divided into a living platform and a production platform. The living platform is 28 m long and 25 m wide, with four main pile legs. The deck is about 10 m away from the sea, and the water depth is 12 m. The technical personnel of the platform conducted modal analysis and calculated the natural frequency of the platform about 1 Hz. During its 10 years life span, the CB246A offshore platform has continually been under complex load conditions. In addition to being corroded by seawater and loaded by strong winds, collisions with passing ships have occurred from time to time. It is of vital importance that the effects of the long term loading, from sea and air, as well as the effects of impacts that occur from time to time, are understood in terms of the long and short term effects to the behavior of the structure.

4.2 Description of the experiment

To verify the effectiveness of the proposed scheme, field experiments were carried out on the CB246A offshore platform of Shengli Oilfield in Dongying on November 30, 2019. The purpose of the experimental study was to use an accelerometer to continuously acquire the platform response under external force. The accelerometer used in this experiment can output high precision triaxial acceleration information in vibration environment and non-uniform magnetic

field environment. The device integrates compensation for temperature, three-dimensional installation error and cross-axis effect of sensor, and supports a high update rate up to 2000 Hz. The main performance parameters are shown in Table 1. The acceleration data sampling frequency was set at 100 Hz, and the time was consistent with the GPS cycle seconds. The X axis corresponded to the north direction, and the Y axis compared to the east direction. Two ship impact tests were conducted at local time 13:23 and 13:27. The ship impacted the southwest leg of the platform in the form of berthing. HHT and FFT are used to analyze the two impacts' vibration response and impact time in detail. The dynamic displacement of the structure is reconstructed using accelerometer data. Through the analysis of acceleration time series and its local amplification, the acceleration sensor can accurately record the instantaneous increase of acceleration at the moment of collision, which gives evidence of its sensitivity and accuracy to the transient response.

5 Results and analysis

5.1 Original data analysis

The original sequence of accelerometers in the two collision experiments is shown in Fig. 8. Due to the influence of serious noise, it is difficult to distinguish the accurate collision time and extract useful information. The sampling frequency of the accelerometer is 100 Hz. According to the Nyquist theorem, a frequency below 50 Hz can be detected. As shown in Fig. 9, the original signal shows multiple main amplitudes through FFT analysis, mainly concentrated in the range of 10–30 Hz, caused by high-frequency noise. According to the previous investigation, the natural frequency of the offshore platform is about 1 Hz. It is necessary to denoise the original data using the method based on the standard scale cumulative modulus mean of formula 3. Taking the X-axis acceleration signal as an example, after EMD decomposition, it is divided into 16 IMF components and one residual,

Table 1 Performance parameters of MTi300 accelerometer

Indicators	Accelerometers	
	Typical	Max
Standard full range	50 m/s ²	—
Bias repeatability(1 yr)	0.03 m/s ²	0.05 m/s ²
In-run bias stability	40 µg	—
Bandwidth(− 3 dB)	375 Hz	N/A
Noise density	80 µg/√Hz	150 µg/√Hz
g-sensitivity(calibrated)	N/A	N/A
Non-orthogonality	0.05 deg	—
Non-linearity	0.03%FS	0.5%FS

Fig. 8 Original acceleration sequence

Fig. 9 Spectrum analysis of original acceleration signal

as shown in Fig. 10. The correlation coefficient (Fig. 11) is calculated to obtain the local minimum at the third IMF component for the first time. Therefore, the first three components are removed as high-frequency noise, and the residual component and residual term are reconstructed to obtain the acceleration sequence after noise elimination.

The denoised acceleration sequences of two collision simulation experiments are shown in Fig. 12. The accelerometer data, after de-noising can identify accurately the time the deformation occurred caused by the collisions. The acceleration sequences of X-axis and Y-axis increase instantaneously twice, and the acceleration of X-axis is the most obvious, which indicates that the structure is greatly affected by the north direction vibration. The first collision time is 13:23, corresponding to GPS weekly seconds: 537,798–537,857; the second collision time is 13:27, corresponding to GPS weekly seconds: 538,038–538,097. It is noted that from the acceleration time series of X and Y axes that the collision time is within the recorded time range. Due to the

Fig. 10 EMD multiscale decomposition of acceleration series

low vertical accuracy and structural stiffness, the dynamic response is not obvious and unstable, so this paper will not discuss the vertical dimension in detail.

5.2 Vibration analysis of collision experiment

After de-noising, the acceleration signal was analyzed using the HHT. From the Hilbert spectrum of X-axis and Y-axis in Fig. 13, two dynamic responses can be seen, with approximate time tags of 220 s and 470 s, corresponding to 13:23 and 13:27, consistent with the time recorded in the

Fig. 11 Relationship between scale and the mean of standardized accumulated modes

Fig. 12 Acceleration time series of X (North) and Y (East) axes in the first collision

experiment. The frequency response range caused by the two collisions is between 1 and 2 Hz. It can be seen from the second impact that the energy is gradually weakened, which indicates that the platform is impacted instantaneously and experienced a short transition from strong to weak. Since the Hilbert spectrum of the collision event is strip-shaped, corresponding to the time point, it is confirmed that the dynamic response of the platform to the collision is short and high frequency. However, the Hilbert spectrum of Z-axis is relatively disordered and cannot analyze the effective information. Two peaks can be seen from the energy spectrum (Fig. 14), and the corresponding time is also consistent

(a) The X-axis (North) Hilbert spectra.

(b) The Y-axis (East) Hilbert spectra.

Fig. 13 The X-axis (a) and Y-axis (b) Hilbert spectra of the two collision events

with the Hilbert spectrum, which confirms that the energy increases when the collision occurs. No larger energy value is found at other time points. This gives evidence that the energy increases are caused by the collision events. From the Hilbert spectrum and energy spectrum, it can be concluded that the frequency response and the energy of the second collision are higher.

Figure 15 shows the marginal spectrum of x -axis and y -axis, and the maximum vibration frequency in collision events can be obtained as 1.5 Hz. Further, FFT is used to extract the frequency of two collisions and analyze the primary amplitude and frequency response in detail. During the first collision, the de-noising acceleration sequence and frequency extraction of x -axis and y -axis are shown in Figs. 16 and 17. From the denoised acceleration sequence, it can be clearly seen that the acceleration value increases

(a) The X-axis (North) energy spectra.

(b) The Y-axis (East) energy spectra.

Fig. 14 The X (a) and Y-axis (b) energy spectra of the two collision events

instantaneously due to the ship collision with the platform. By comparing Fig. 16a with Fig. 17a, it can be seen that the collision instantaneous acceleration value of x -axis is greater than that of y -axis, and the platform is subject to large noise in Y -axis (east direction). The x -axis vibration frequency extracted from the collision event is 1.477 Hz (Fig. 16b, which is slightly less than 1.492 Hz of the y -axis (Fig. 17b). The results show that the x -axis of the platform is greatly affected by the North vibration, and the frequency response of the platform is small when the acceleration value is large. The same results are also reflected in the second collision (some figures are omitted here). The frequencies of the two axes are 1.483 Hz and 1.498 Hz respectively. Compared with the marginal spectrum (Fig. 15), the extraction frequency of FFT spectrum is lower, but the calculation amplitude is higher than the marginal spectrum.

(a) The X-axis (North) marginal spectra.

(b) The Y-axis (East) marginal spectra.

Fig. 15 The X-axis (a) and Y-axis (b) marginal spectra of the two collision events

5.3 Displacement reconstruction

The accelerometer is more sensitive to high-frequency information than other sensors used for platform monitoring (i.e. GNSS) and can accurately record the forced high-frequency vibration of the structure. Therefore, the high-frequency dynamic displacement of the structure is obtained by integrating the acceleration data through bandpass filtering and eliminating the linear part. In this paper, the north direction of two collision events is analyzed as an example. Figure 18 describes the comparison between the high-frequency part of GNSS and the high-frequency dynamic displacement obtained by the accelerometer. Two collisions can be clearly seen in the reconstructed accelerometer dynamic displacement. The amplitude of the first impact is 1 mm, and that

(a) X-axis (North) de-noising acceleration time series.

(b) X-axis (North) frequency spectrum.

Fig. 16 X-axis frequency extraction in the first collision

of the second is 1.5 mm. It can be seen that the overall amplitude of GNSS is large, and the high-frequency displacement of GNSS and acceleration reconstruction has a deviation. This is because the offshore platform is affected by the complex environment, and the accuracy of the long baseline is limited. GNSS does not effectively extract the high-frequency dynamic displacement of the structure.

The comparison between the displacement obtained from the acceleration of the two collision events and the GNSS displacement is shown in the partial enlarged Fig. 19. The overall trend of the two kinds of data is roughly the same, but there is some deviation. The displacement of GNSS data increases at the collision time recorded by the accelerometer. Still, the amplitude is smaller than that obtained by the accelerometer, and the amplitude will increase at other times. The results show that the accelerometer is suitable for monitoring the dynamic response of the structure in collision

(a) Y-axis (East) de-noising acceleration time series.

(b) Y-axis (East) frequency spectrum.

Fig. 17 Y-axis frequency extraction in the first collision **Fig. 18** Comparison of accelerometer reconstructed displacement and GNSS displacement

(a) Comparison of first impact displacement.

(b) Comparison of second impact displacement.

Fig. 19 Partial enlargement of acceleration integral displacement and GPS displacement

events. GNSS is affected by long-baseline monitoring of offshore platforms, and its accuracy is low. In addition, the instability of 4G transmission signal is easy to cause data loss, which is not suitable for offshore platform structural health monitoring.

6 Conclusion

China's offshore oil development is in a new period of rapid development. It is necessary to monitor the offshore platform by reasonable means. In this paper, we used accelerometers to monitor the structure of an offshore platform. Through the combination of HHT and FFT, the dynamic response of the two collision simulation experiments is analyzed in detail. The vibration frequency of the platform structure is

successfully extracted, which lays the foundation for further research in the future. At the same time, the accelerometer data post-processing technology is used to denoise and integrate the acceleration data, and the dynamic displacement is reconstructed. Compared with the displacement measured by GNSS, the advantage of the accelerometer in offshore platform structure detection is verified. The health monitoring of offshore platforms has become an urgent task and has broad development prospects. It is necessary to develop new methods to ensure the safe operation of these marine assets.

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