

Article ID: 1007-7294(2025)06-0941-11

## Monitoring and Data Analysis of Mooring Tension for Floating Platforms

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**Abstract:** Mooring cable tension is a crucial parameter for evaluating the safety and reliability of a floating platform mooring system. The real-time mooring tension in an actual marine environment has always been essential data that mooring system designers aim to acquire. To address the need for long-term continuous monitoring of mooring tension in deep-sea marine environments, this paper presents a mooring cable tension monitoring method based on the principle of direct mechanical measurement. The developed tension monitoring sensors were installed and applied in the mooring system of the "Yongle" scientific experimental platform. Over the course of one year, a substantial amount of in-situ tension monitoring data was obtained. Under wave heights of up to 1.24 m, the mooring tension on the floating platform reached 16.5 tons. Through frequency domain and time domain analysis, the spectral characteristics of mooring tension, including wave-induced force, slow drift force, and mooring cable elastic restoring force, were determined. The mooring cable elastic restoring force frequency was approximately half of that of the wave signal. Due to the characteristics of the hinge connection structure of the dual module floating platform, under some specific working conditions the wave-induced force was the maximum of the three different frequency forces, and restoring force was the smallest.

**Key words:** floating platform; mooring tension; tension monitoring sensor; wave frequency force; drift force

**CLC number:** P75      **Document code:** A      **doi:** 10.3969/j.issn.1007-7294.2025.06.008

### 0 Introduction

Mooring systems are used to restrict the movement of floating platforms at sea and the failure of a mooring system can cause the sinking, tilting, or collision with the surrounding objects, of the floating platform, resulting in significant economic losses and societal impacts<sup>[1]</sup>. Mooring cables are crucial components of mooring systems, which provide tensions to floating platforms, and the tensions must be within the specified design index<sup>[2-3]</sup>. Mooring cables endure the alternating tension loads caused by waves and ocean currents over a long period in the sea. Under adverse conditions such as ocean storms and typhoons, the dynamic tension of mooring lines becomes greater, and the possibility of exceeding the design load of a mooring system is also higher<sup>[4-6]</sup>. Continuous online monitoring of mooring tension can master the

Received date: 2024-12-25

Foundation item: Supported by the Research Project of High-Tech Ships from Ministry of Industry and Information Technology of China ([2019]No.357)

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safety status of a mooring system in real time, which is helpful to assess the safety margin of the mooring system. It can prevent damage or even breakage of mooring cables during prolonged use, and provide real marine load data for optimizing the design of mooring systems, ensuring platform safety<sup>[7-8]</sup>.

Currently, the primary technologies for monitoring mooring cable tension in a marine environment include inclinometer measurement based on underwater acoustic communication or self-contained and stopper pressure measurement. The inclinometer measurement method is the most commonly used in mooring tension measurement projects, but this method indirectly calculates tension using the catenary equation, which has relatively a large error and a lack of data details due to the complex marine environment. For example, the UK-based offshore engineering company 2H employs an ultrasonic angle measurement device to measure and transmit mooring chain tension. An underwater inclinometer is installed on the mooring chain to measure the inclination angle and an underwater ultrasonic receiver device is used to receive wireless tension measurement data, which is transmitted to the monitoring system computer via a communication cable. Due to the limitation of underwater acoustic communication, the frequency of tension collection is very low and cannot capture high-frequency wave impact information. On the other hand, this ultrasonic inclination measurement system is complex to use, expensive, and difficult to promote and apply. Feng et al<sup>[9]</sup> developed and applied a self-contained mooring tension monitoring device based on inclination measurement, while the tension data is saved under water and cannot be transmitted to computer in real time. Additionally, the self-contained measurement system cannot achieve high-speed long-term measurement due to power consumption issues, and data cannot be obtained in real time, which poses obstacles to timely analysis of data and evaluation of mooring system status. Du et al<sup>[10]</sup> studied on method for tensile measurement of stud-less mooring chain based LVDT sensor, but the linearity was poor. Another major traditional method for mooring tension measurement is the pressure measurement method of the chain stopper, but it can only measure quasi-static force, and cannot collect dynamic wave force. Based on the analysis of the development of tension monitoring technology and the requirement for comprehensive acquisition of mooring tension in practical engineering, the development of direct mooring tension monitoring technology with reliable environmental adaptability and high sampling frequency has good application prospects<sup>[11]</sup>.

Due to the unique nature of deep-sea marine environments and the working characteristics of mooring cables, there are significant challenges in achieving long-term continuous real-time monitoring of mooring tension. Based on a comprehensive survey of the operating environment of floating platforms and the composition of mooring cables, China Ship Scientific Research Center has developed a monitoring sensor of mooring tension based on the direct mechanical measurement principle. As shown in Fig. 1, this tension monitoring sensor is closely attached to the shackle in a "wrist-style" installation, offering advantages such as a compact size, water tightness, convenience in use, and suitability for a maximum depth of up to 100 m in marine environment.

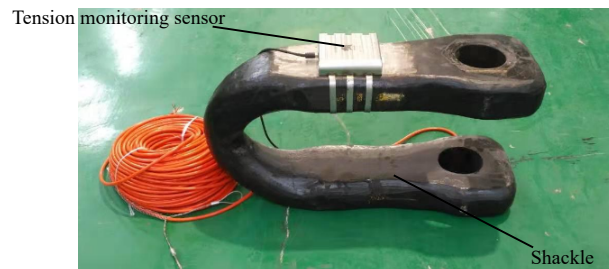


Fig.1 Mooring tension monitoring sensor

## 1 Tension measurement principles and mechanical analysis

As shown in Fig. 2, a mooring cable is typically composed of two segments connected through a

shackle. The shackle bears the tension of the cable on both ends. For the tensioned segment of the cable, the internal tension direction of the mooring cable is parallel to the axis of the cable. According to mechanics, the tension applied on the connecting shackle is the same as that on the mooring cable. Therefore, the tension of the mooring cable can be obtained by measuring the tension of the shackle. The changes of mooring tension are detected by strain sensors installed on the shackles in this paper.

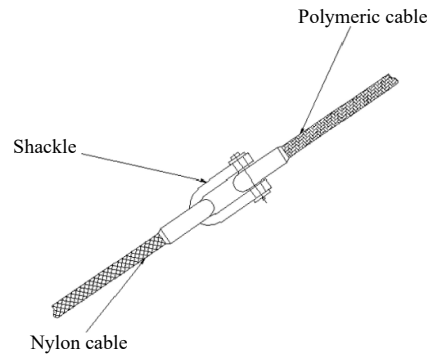


Fig.2 Composition of mooring cables

The mooring cable shackle consists of a D-shaped main body, a pin shaft, and a fastening nut. The pin shaft and the D-shaped main body are in interference fit, allowing the pin shaft and the D-shaped main body to be treated as a single unit for force analysis. The external forces acting on the D-shaped shackle are illustrated in Fig. 3.

The force state of the connecting shackle, as illustrated in Fig. 3, can be further represented equivalently as depicted in Fig. 4.

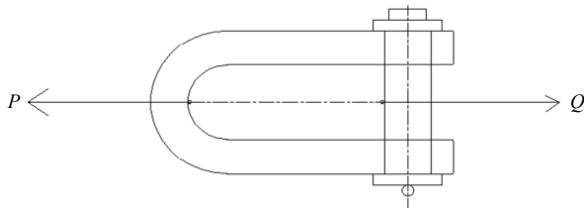


Fig.3 Force state of the connecting shackle

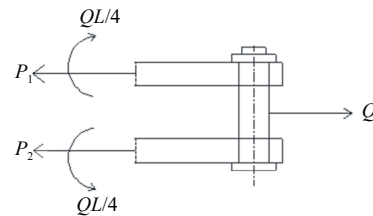


Fig.4 Equivalent force diagram of the shackle

From force balance, it can be obtained that

$$P_1 = P_2 = \frac{Q}{2} \tag{1}$$

where  $P_1$  and  $P_2$  are the tensile forces in the shackle arms,  $Q$  is the vertical force of the axis pin.

According to the force principle diagram, it can be observed that the two arms of the shackle bear bending moment loads and tensile force loads. Correspondingly, there are bending and tensile stresses within the shackle arms. The bending moment load acting on the shackle arm is  $QL/4$ , resulting in bending stress (negative strain); the axial tensile force is  $Q/2$ , resulting in tensile stress (positive strain). According to materials mechanics knowledge, the surface structural stress on the shackle arm can be expressed as:

$$\sigma = \frac{Q}{2A} - \frac{QL}{4I_z} y_{\max} \tag{2}$$

Further,  $\sigma = E\varepsilon$ , the following Eqs. (3) and (4) can be derived:

$$\varepsilon = \frac{Q}{2EA} - \frac{QL}{4EI_z} y_{\max} \tag{3}$$

$$Q = \frac{4EI_z}{2I_z - ALy_{\max}} \varepsilon \tag{4}$$

When  $y_{\max} = \frac{h}{2}$ , Eq. (5) can be derived:

$$Q = \frac{8EI_z}{4I_z - ALh} \varepsilon \tag{5}$$

where,  $\sigma$  represents the surface structural stress on the shackle arm,  $A$  means the cross-sectional area of the shackle arm,  $I_z$  represents the moment of inertia of the shackle arm section,  $L$  is the span of the shackle,  $E$  is the elastic modulus of the shackle material,  $h$  means the thickness of the shackle arm, and  $\varepsilon$  is the structural strain.

For D-shaped shackle, the values of  $A$ ,  $I_z$ ,  $L$ ,  $E$ , and  $h$  are all known, thus the expression  $\frac{8EA I_z}{4I_z - ALh}$  is a constant. From Eq.5, it is evident that the mooring cable tension  $Q$  is directly proportional to the structural strain  $\varepsilon$  of the shackle arm. Therefore, by measuring the structural strain of the shackle arm, the tension load in the mooring cable can be obtained through calibration.

Based on the force characteristics and considerations for reliable measurements, a point-welded full-bridge unidirectional strain gauge is selected as the sensitive component. For the convenience of arranging the strain-sensitive component and ensuring long-term protection, the center position in the D-shaped shackle single arm symmetry axis is determined as the installation location for the sensitive component. The schematic diagram of the strain sensor installation is shown in Fig. 5.

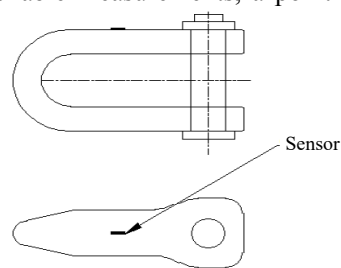


Fig.5 Position of strain sensitive component

## 2 Experimental validation and calibration

The mooring tension monitoring sensor developed is used for the mooring cable as shown in Fig. 2. The mooring cables are soft nylon and polymeric cables with a small-sized connecting ring, and the forces caused by torsion, bending, and eccentricity phenomena are relatively small compared to axial tension. In addition, the operators of the mooring system regularly release the twisting phenomenon of the mooring cable through the anchor machine. Therefore, only axial tension conditions are considered during calibration experiment.

To obtain the calibration coefficient of the mooring tension sensor and verify its linearity, tension loading calibration tests were conducted at the Structural Strength Testing Laboratory of China Ship Scientific Research Center.

Experimental equipment: One 300-ton horizontal tension testing machine, two D-shaped shackles equipped with tension monitoring sensors, two strain data collectors, one computer, and a set of supporting communication and power cables.

Prior to the experiment, according to the tension testing scheme depicted in Fig. 6, the mooring tension sensor, fixtures, and testing equipment were installed and connected. During the experiment, the testing machine was incrementally loaded in the sequence of 0 t  $\rightarrow$  5 t  $\rightarrow$  10 t  $\rightarrow$  20 t  $\rightarrow$  ...  $\rightarrow$  190 t, maintaining each load level for 1 min. The strain data collector continuously recorded the structural strain and corresponding tension in the experiment. Each D-shaped shackle underwent three tension tests, and the loading and data collection were cyclically repeated. The actual site of the mooring tension monitoring sensor tension test is shown in Fig. 7.

Based on the structural strain and tension data from the two tension monitoring sensors, linear regression fitting was performed using the least squares method. The regression curves for each tension monitoring sensor are shown in Fig. 8, with the horizontal axis representing structural strain (in  $\mu\varepsilon$ ) and the vertical axis representing tension load (in tons). The linear calibration coefficients are listed in Tab. 1.

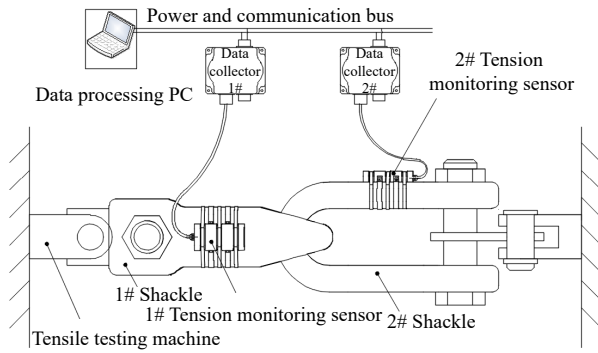


Fig.6 Schematic diagram of the tension monitoring sensor test verification



Fig.7 On-site mooring tension monitoring sensor tension test

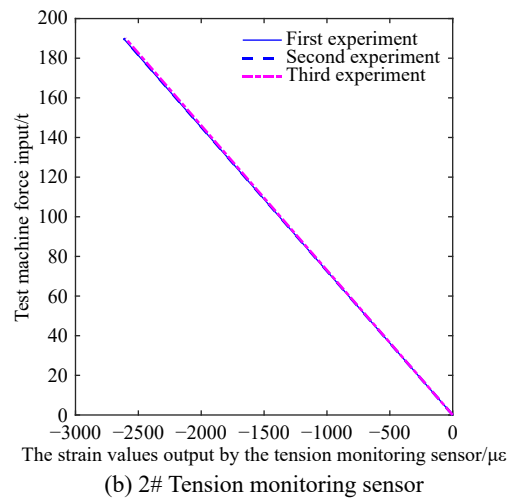
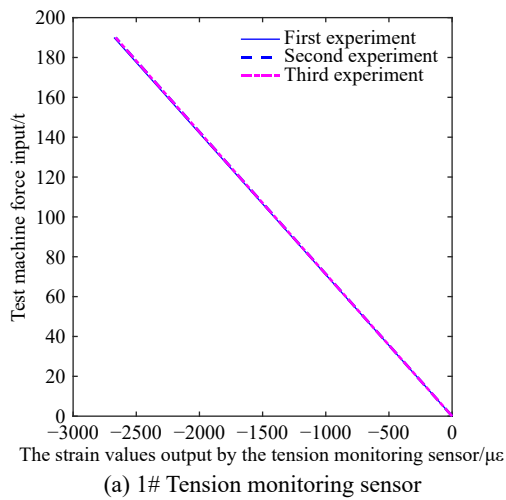


Fig.8 Regression curves for each tension monitoring sensor

Tab.1 Linear calibration coefficients and repeatability of tension monitoring sensors

| Tension monitoring sensor number |              | 1#        | 2#      |
|----------------------------------|--------------|-----------|---------|
| Linear coefficient               | First trial  | -0.0710   | -0.0726 |
|                                  | Second trial | -0.0713   | -0.0727 |
|                                  | Third trial  | -0.0713   | -0.0730 |
| Standard deviation               |              | 0.000 875 |         |
| Mean value                       |              | -0.072    |         |

From Tab. 1 and Fig. 8, the regression linear coefficients of the mooring tension sensors indicate excellent linearity and repeatability. Moreover, the linear coefficients of the two sensors are nearly identical, with a standard deviation of only 0.000 875. The calibration tests demonstrate that the proposed tension monitoring method is feasible and capable of directly measuring mooring tension loads.

### 3 Monitoring implementation

The "Yongle" scientific experimental floating platform consists of two modules: main module and auxiliary module, connected through hinges of pin shaft connector<sup>[12]</sup>. The main parameters of Yongle<sup>[13]</sup> scientific experimental platform are listed in Tab. 2. The mooring arrangement of the floating platform is

illustrated in Fig. 9. There are totally 8 cables, labeled L1 to L8, with two parallel mooring cables placed at each corner of the platform. Each mooring cable comprises three parts: a bottom anchor chain, a nylon cable, and a polymeric cable. The bottom anchor chain is located on the seabed, the nylon cable is connected to the bottom anchor chain through a shackle while the upper part of the nylon cable is connected to the polymeric cable through a D-shaped shackle. The polymeric cable is guided through a pulley and connected to the anchor winch device on the floating platform for tensioning and releasing the mooring cables.

**Tab.2 Main parameters of Yongle scientific experimental platform**

| Parameter/unit         | Value | Parameter/unit   | Value               |
|------------------------|-------|--|---------------------|
| Length overall $L/m$   | 63.0  | Length from the center of gravity to the tail of the platform $L_{CG}/m$ | 31.5                |
| Breadth $B/m$          | 25.0  | Height from the center of gravity to the water surface $H_{CG}/m$        | 1.965               |
| Depth $D/m$            | 14.2  | Roll moment of inertia $I_{xx}/(kg.m^2)$                                 | $3.464 \times 10^8$ |
| Gross Tonnage $M/t$    | 3655  | Pitch moment of inertia $I_{yy}/kg.m^2)$                                 | $1.456 \times 10^9$ |
| Designed draft $T_d/m$ | 5.5   | Bow roll moment of inertia $I_{zz}/(kg.m^2)$                             | $1.572 \times 10^9$ |

Four tension monitoring sensors are placed on the mooring cables at the corners labeled L1, L4, L5, and L8 for monitoring the mooring cable tensions in real time. After installation, the tension monitoring sensors are located approximately 15 m below the sea surface. The sensing signal of tension monitoring sensor is transmitted to the strain data collector on the floating platform through communication cables. The strain data collector is connected to the monitoring computer via the CAN bus. The monitoring computer collects real-time tension signal from the mooring system and synchronously transmits the tension data to the control center computer of the floating platform. The monitoring computer transmits tension data through the 4G mobile network to the internet for remote users' access to mooring tension data. Remote users can view real-time tension and historical data through a mobile application software. The mooring tension monitoring implementation plan for the scientific experimental floating platform is depicted in Fig. 10.

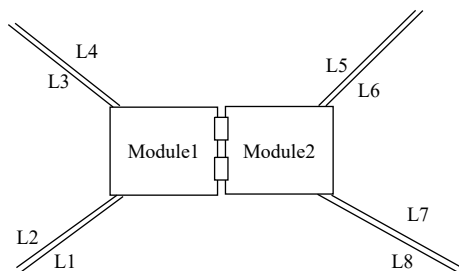


Fig.9 Mooring arrangement for the "Yongle" floating platform

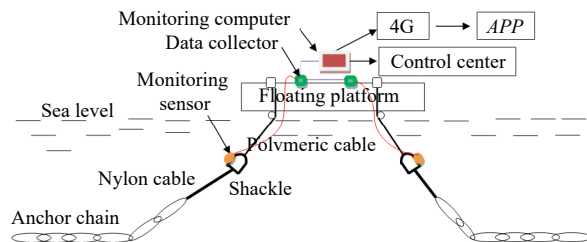


Fig.10 Implementation plan for mooring tension monitoring of the floating platform

Following the implementation plan as shown in Fig. 10, the mooring tension monitoring system was established. The on-site photo of the system after the arrangement of the mooring tension monitoring system is shown in Fig. 11. The implementation of the mooring tension monitoring system does not adversely affect the normal operation of the mooring system. The mooring tension monitoring system operates at a sampling frequency of 50 Hz. The monitoring computer provides real-time display of tension data and curves, stores continuous monitoring data, and generates alarm messages when the mooring tension exceeds the design value. Fig. 12 shows the real-time tension curve during the operation of the mooring tension monitoring system.

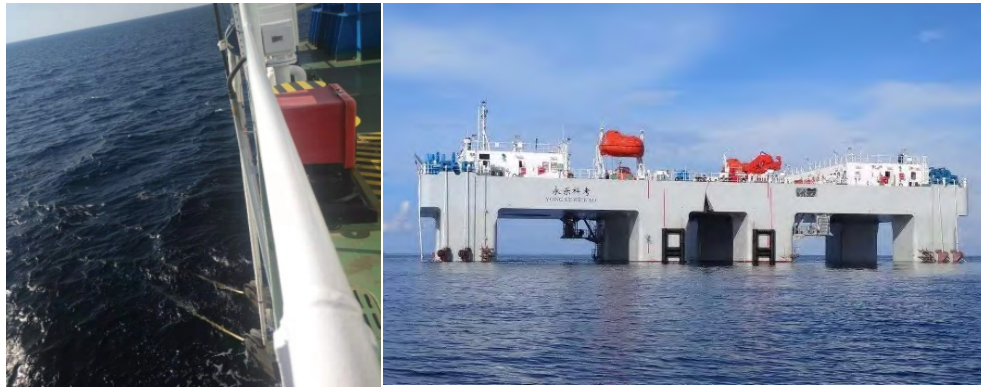


Fig.11 On-site mooring cable tension monitoring for the floating platform

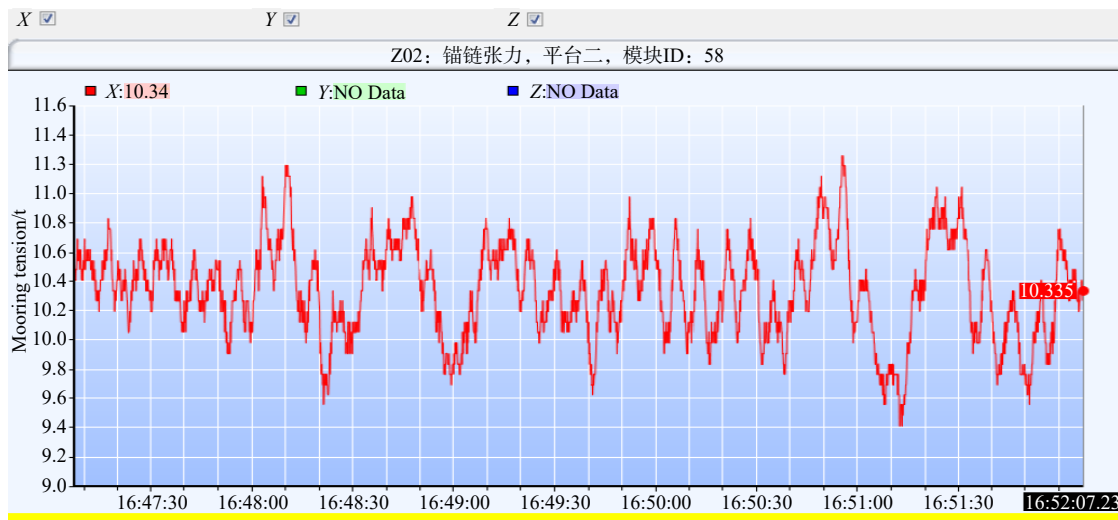


Fig.12 Real-time tension monitoring curve

### 4 Data analysis

The wave height variation curve is shown in Fig. 13, in the surroundings of the floating platform during the period from 11:00 on September 5, 2019, to 23:30 on September 7, 2019. During this period a typhoon was passing through, with an average significant wave height of over 0.8 m, a maximum significant wave height of 1.24 m, and a period of 7.14 s. The wave height data was obtained from the "Wave Rider" measurement device, with a wave measurement interval of 30 min.

Based on the statistical data of wave height, it is observed that the maximum significant wave height during the typhoon was 1.24 m. The tension monitoring data during the maximum wave height period, specifically from 00:00 to 04:00 on September 6, 2019, was extracted. Fig. 14 shows the mooring cable tension variation curve during the 4-hour period of maximum wind and wave conditions, with maximum mooring tension of 16.54 t. Fig. 15 shows the dynamic

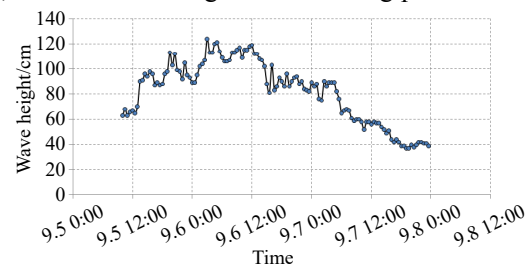


Fig.13 Significant wave height curve during the passage of the typhoon

components of mooring tension within a 10-minute interval around the moment of maximum significant wave height. From Fig. 14, it can be observed that the tension signal recorded is complete during the continuous 4-hour period, with a normal signal waveform, no interference or distortion points, and good data quality. It truly reflects the changes of mooring cable tension in the ocean environment with strong winds and huge waves. In Fig. 15, mooring tension exhibits a clear periodicity and is superimposed with multiple load waveforms, showing a relatively slow rate of change.

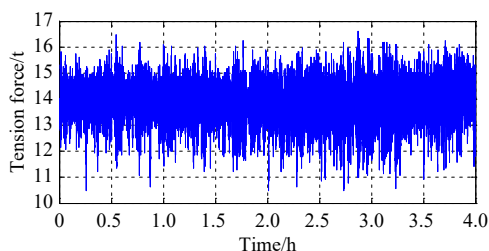


Fig. 14 Time-course curve of the tension for a continuous 4 hours

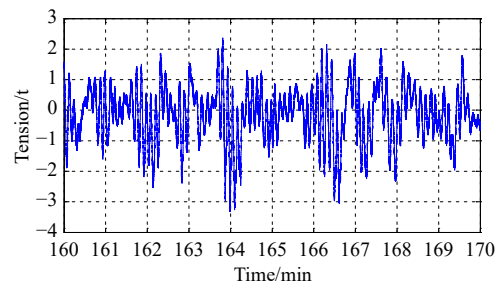


Fig. 15 10-minute time-course curve of the dynamic tension during maximum wave

To further analyze the correlation between the mooring tension and wave loads, as well as the characteristics of tension variation, the tension signal for the 4-hour period was subjected to FFT transformation to obtain the frequency spectrum characteristics. From the frequency spectrum of the mooring tension signal in Fig. 16, the primary components of the tension signal are distributed in the frequency ranges of 0 Hz to 0.09 Hz and 0.09 Hz to 0.23 Hz. The former includes a maximum component corresponding to 0.035 Hz caused by the slow drift of the platform, with a period of 28.6 s while the latter includes a maximum component corresponding to 0.14 Hz caused by the wave load, with a period of 7.14 s. The tension amplitude at 0.035 Hz caused by the slow drift of the platform is larger than that at 0.14 Hz caused by wave load.

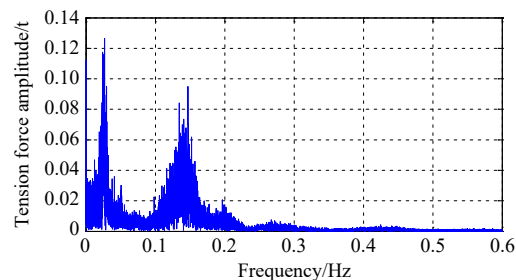


Fig. 16 4-hour FFT spectrum of the dynamic tension

In order to compare the components of various signals in the time domain in more detail, the mooring tension signals were decomposed into two parts: the slow drift signal of the floating platform and the wave signal, and displayed in the same figure. Fig. 17 presents a comparison of different signal components of dynamic mooring tension in ten minutes. Before the comparison, the original signal was processed in zero-mean, eliminating the static tension component. The blue curve in the figure represents the original tension, which is mainly composed of slow drift response component (0 to 0.09 Hz) and wave response component (0.09 to 0.23 Hz). It can be observed in Fig. 17 that when the significant wave height is 1.24 m, the maximum dynamic tension response of the platform mooring line is about 5.6 t in full amplitude. The maximum full amplitude tension of the slow drift response component is about 2.9 t, and the maximum full amplitude tension of the wave response component is about 3.7 t. The tension data obtained show that the wave force is greater than the drift force, which is different from the general rule of signal component proportion in traditional mooring tension mechanics. By analyzing the structure of "Yongle" floating platform, it is found that the floating platform is composed of two independent small platform modules connected by hinges. Under the action of wave force, the two modules rotate relatively at the same frequency

as the wave, causing the tension in mooring cable to increase, resulting in the wave force being greater than the slow drift force. It is significantly different from the characteristics of mooring tension component proportion of general integral platform structures.

By observing the slow drift component (0 to 0.09 Hz) curve in Fig. 17, it is noted that there is a small amplitude periodic change signal in the curve. In order to refine the 0~0.09 Hz signal, it is decomposed into two sub intervals: 0~0.04 Hz and 0.04~0.09 Hz. In Fig. 18, the original tension signal is decomposed into three frequency characteristic components for comparison. It can be observed that the green curve (0.04 to 0.09 Hz) shows complete sinusoidal characteristics, and its frequency is lower than the wave frequency but higher than the slow drift frequency. Considering the composition of the mooring cable, the sensor installation section is made up of high molecular weight cable and nylon cable, both possessing good elasticity. In a wave environment, there is an inherent physical property of elongation and recovery for mooring cable. The signal component (0.04 to 0.09 Hz) shall be the elastic wave restoring force in the mooring cable, its frequency is approximately 0.067 Hz, roughly half of the wave frequency (0.14 Hz).

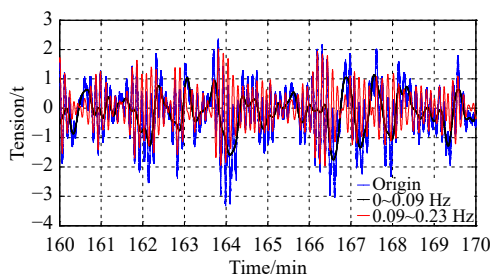


Fig.17 Comparison of slow drift signal, wave signal, and original signal

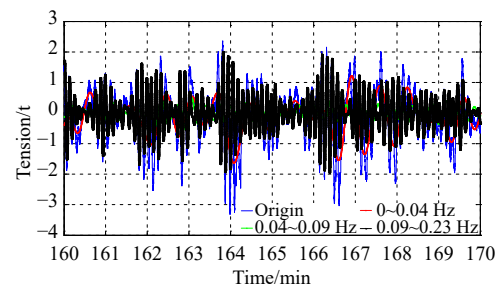


Fig.18 Comparison of slow drift component, wave component, mooring cable elastic component, and original signal

In Fig. 18, the blue curve represents the original signal, the red curve (0 to 0.04 Hz) represents the slow drift component, the green curve (0.04 to 0.09 Hz) represents the mooring cable elastic component, and the black curve (0.09 to 0.23 Hz) represents the wave component. From the waveform curves of signals at different frequencies, it can be observed that the high-frequency tension component aligns with the wave frequency, indicating that the up and down movements of the waves cause the mooring cable to tighten and slacken, constituting the primary component of mooring tension. Simultaneously, there is a slow tightening and slackening phenomenon, superimposed on the wave force. This force is due to the slow drift of the platform itself rotating around the mooring point. The small waveform superimposed on the slow drift signal is caused by the elasticity of the mooring cable. Furthermore, the small waveform superimposed on the slow drift indicates that the mooring cable possesses good elasticity.

## 5 Concluding remarks

The feasibility of the proposed mooring line tension monitoring method is verified by mechanical analysis and laboratory tension calibration experiments. The experimental results show that the developed tension monitoring sensor has good linear coefficient and repeatability, and meets the performance requirements of tension sensors. According to the structural characteristics of floating platforms, the implementation scheme of mooring tension monitoring is designed, the developed tension monitoring sensor is applied to the actual marine environment, and the mooring tension monitoring system is established. After

a year of practical application, the tension monitoring system has shown stable and reliable performance and obtained a lot of useful data. Through the analysis of tension monitoring data, the characteristics of mooring cable tension variation in a real complex marine environment are obtained. Notably, the frequency of mooring cable elastic recovery forces is approximately half of the wave signal. Due to the characteristics of the hinge connection structure of the double module floating platform, the wave force is greater than the drift force, which is different from the overall platform structure. The data analysis in this paper provides an objective basis for the study of dynamic behavior of mooring system, and will provide assistance for the optimal design and operation strategy of "Yongle" scientific experimental platform.

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## 浮动平台系泊张力监测及数据分析研究

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**摘要:** 系泊缆绳张力是评价浮动平台系泊系统安全性和可靠性的重要参数, 真实海洋环境下的系泊张力一直是系泊系统设计人员想要获取的重要数据。针对深海海洋环境下系泊张力需要长期连续监测的问题, 本文研究出一种基于力学直接测量原理的系泊缆绳张力监测方法, 并将研制的张力监测传感器在“永乐号”科学试验平台系泊系统上进行了安装应用。在1年使用期间, 获得了大量实际海况张力监测数据, 在1.24 m浪高下浮动平台系泊张力达到了16.5 t; 通过频域和时域分析方法得到了系泊张力包含的波浪力、慢漂力和系泊缆弹性恢复力频谱特征, 系泊缆弹性恢复力频率约为波浪信号的1/2; 由于“永乐号”科学试验平台两个子模块之间为铰链连接方式, 在时域上系泊力中的波浪力大于慢漂力, 弹性恢复力最小。

**关键词:** 系泊张力; 张力监测传感器; 波频力; 波浪慢漂力; 频谱特征

**中图分类号:** P75      **文献标识码:** A

**基金项目:** 工信部高技术船舶科研项目(工信部装函(2019)357号)

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