

Design of a Cable Deployment and Retrieval System for a 1500-Meter Marine Winch

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Abstract: To investigate the stress distribution and dynamic variation patterns of deep-sea winch systems during submersible cable towing operations and ensure operational safety, a novel dual-specification winch compatible with two distinct cable types was designed. The technical scheme, structural characteristics, and key parameters of the winch are introduced in detail. Simulation analyses are conducted based on both the physical model and the numerical simulation model established for the cable storage winch and cable management system. A systematic analysis of the stress and deformation of the cable storage winch and cable management system is carried out to verify the accuracy of the proposed models, providing a theoretical reference for the mechanical design and optimization of deep-sea winch systems.

Keywords: Ocean winch, cable retraction system, design features, finite element analysis.

1. Introduction

With the continuous growth of the global economy, the exploitation of nearshore resources has approached its limits, leading to gradual depletion. As a result, seabed resource exploration, deep-sea scientific investigation, and deep-sea archaeology have become increasingly important. Marine winch systems, which play a critical role in ocean exploration, refer collectively to various types of winches used for storing and deploying cables during scientific research operations at sea.[1]The development of marine winches can be traced back to the late 19th century, with a history spanning over a hundred years. With the advancement of ocean exploration and marine engineering, winch technology has gradually become an essential tool in marine scientific research, resource exploitation, and offshore operations.[2] In terms of classification, scientific research winches are mainly categorized into cable management winches, traction winches, remotely operated vehicle (ROV) winches, and hydrographic winches.

2. Integrated Structural Design of the Marine Winch

2.1. Winch Design Specifications

Marine scientific winch systems primarily serve to deploy and retrieve oceanographic equipment.[3] Due to the severe operational conditions at sea—including variable weather, wave impacts, complex marine environments, and technical constraints—the design must address challenges posed by extreme weather, hazardous sea states, operational safety risks, and environmental protection. The following critical features and functional requirements must be prioritized:

(1) Ensuring Winch Stability

The winch design must comprehensively account for operational sea states and mechanical structural strength to guarantee safety and reliability during deep-sea operations. The system must withstand its maximum designed load while maintaining stable performance under extreme conditions.[4] Overload protection mechanisms should be integrated to prevent equipment damage from excessive loads. Additionally, synchronized operation between the cable

arrangement system and the storage drum is essential to ensure overall operational stability.

(2) Integration of Tension Monitoring Systems

Real-time monitoring of cable tension is required to enable unimpeded passage of towed cables and hydrophone arrays. Excessive tension may lead to cable rupture, while insufficient tension risks equipment instability or uncontrolled motion. A tension data logging system should be implemented to support maintenance protocols and performance analysis. Precise tension regulation within permissible limits minimizes equipment wear and fatigue, thereby extending service life.

(3) Precision in Cable Arrangement

The cable spooling mechanism, a critical subsystem, must accommodate two distinct cable specifications.[5] This ensures stable positioning of cables on the storage drum during deployment or retrieval, preventing entanglement, jamming, or misalignment.

(4) Operational Safety and Efficiency

To enhance load-handling efficiency, the winch should feature a wide speed-regulation range to adapt to diverse operational demands. The drive motor must exhibit high precision and stability for accurate control of drum rotation speed and output torque, with smooth speed transitions to avoid load oscillations or abrupt halts.[6] Simulation software should be employed to model winch operating conditions and validate structural design rationality.

2.2. Winch parameter design

The deep-sea winch system under investigation is characterized by its operational capability in severe sea conditions and its hybrid cable configuration integrating standard towed cables with fiber-optic towed cables.[7] The structural design must satisfy the following operational parameters:

Applicable Sea State: Operational within Sea State 6;

Cable Specifications: Towed cable: 1,000 m length; Fiber-optic towed cable: 500 m length;

Cable Diameters: Towed cable: 18 mm \pm 0.5 mm; Fiber-optic towed cable: 38 mm \pm 0.8 mm;

Maximum Retrieval/Deployment Speed: \geq 1 m/s for both cable types under rated load;

Maximum Operational Tension: 5 kN (sustained tension during standard operations);
 Redundancy Load Capacity: 6 kN (safety factor of 1.2

relative to operational tension);
 Braking System Specification: 10 kN dynamic braking capacity (200% of operational load).

Table 1. Technical specifications of winch system

Parameter	numerical value
Winch cable storage capacity	≥1500m
Maximum cable retraction speed	≥1m/s
Maximum braking force	≥10kN
Winch power supply	380V three-phase AC power
Winch power consumption	≤15kW
External dimensions of winch	1.6m(H)×1.7m(W) ×2m(L)

2.3. Selection of motor

In order to facilitate the temporary installation of the winch system on the ship, the winch power supply adopts conventional 380V three-phase AC power supply. The maximum working tension of the winch is 5kN, and the maximum retraction speed is 1m/s. Calculate the maximum theoretical power required for the main motor based on this theory:

$$\begin{cases} P = F \times V \\ T_{out} = \frac{P \times 9550}{n_{in}} \\ T_{out} = T_{in} \times i \times \eta \end{cases}$$

Considering factors such as the efficiency loss of the motor and reducer, a motor with a power of 11KW, a speed of 1500rpm, a reducer transmission ratio of 62.55, and an output torque of 4560Nm was actually selected.

The power system of the cable laying unit adopts a 1kW servo motor and reducer power system. The power system drives the screw rod to rotate in both directions to achieve left and right cable laying of the winch. The rated output speed of the power system is 345.3r/min, and the output torque is 25N.m. The total power of the electronic control unit is less than 1kW, and the total power of the winch system is about 13kW,

meeting the requirement of not exceeding 15kW.

2.4. Design of the drum

An appropriate ratio needs to be maintained between the diameter of the cable and the diameter of the drum to ensure smooth cable winding and unwinding. Generally speaking, the diameter of the drum should be at least 10 to 15 times the diameter of the cable. This ratio can be adjusted appropriately according to the operating environment, purpose, and material of the cable to ensure the safe use of the equipment.

Choose a thicker fiber optic cable as the reference object, with an inner diameter of no less than 15 times that of the cable reel. Therefore, choose a cable reel with an inner diameter of 685mm.

Inside span length of the reel

$$L = q \times d \times 1.04$$

The length of the cable tray must be such that the towing cable and fibre optic towing cable winding turns per layer are integers. The diameter of the towing cable is 18 mm, and the winding circle is 57; the diameter of the fibre optic towing cable is 38 mm, and the number of winding circles is 30. Substitution of these values into the formula yields L = 1185.6 mm. According to the requirements for cable storage, the length of the cable tray must be 1190 mm. The concluding determination of the cable disc specifications for the outer circle.

Table 2. Length of storage cable for each layer of towing cable

Number of layers	Diameter (mm)	Length of each storage cable layer (m)
1	701.96	125.7005
2	736.02	129.4874
3	769.89	137.8648
4	804.16	141.4752
5	838.13	150.0846
6	872.35	153.4718
7	906.44	162.3169
Total length		1000.4012

Table 3. Table of Storage Cable Length for Each Layer of Drag Line Array

Number of layers	Diameter (mm)	Length of each storage cable layer (m)
1	958.87	90.3714
2	1037.46	94.5190
3	1111.47	105.0580
4	1185.45	108.0018
5	1259.46	102.8745
Total length		500.8247

According to the design selection and calculation, the cable reel can store 1000m of 18mm diameter towing cables in 7 layers, and 500m of 38mm diameter fiber optic towing array

cables in 5 layers, with a total storage capacity of more than 1500m, meeting the storage requirements of 1500m.

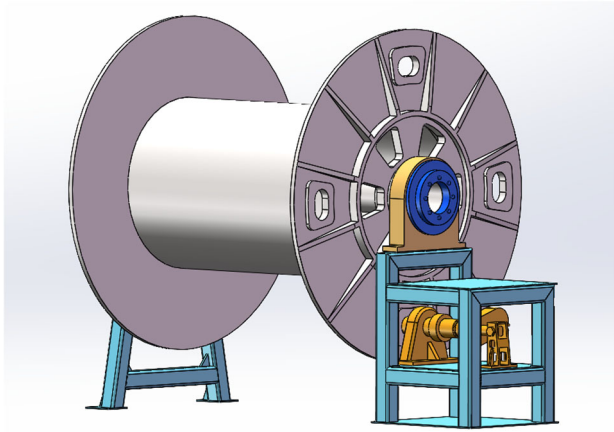


Figure 1. Reel model

The speed of both the cable and the release mechanism are significant indicators of the efficacy of the winch system. They reflect the process of towing, both the cable and the fibre optic towline array, and the speed of the moving line. The indicator directly affects the system's performance efficiency in the execution of tasks. The rate of acceleration is contingent upon the rotational velocity of the cable disc within the winch system, in conjunction with the diameter of the current winding layer comprising the tow cable or towline array. The maximum take-up speed and cable release is defined as the outermost towline array moving line speed under the maximum rotational speed of the cable disc. In accordance with the prevailing work demands, the maximum take-up speed of the winch system is specified at a minimum of 1m/s, while the maximum release speed is also set at this rate. The take-up speed is contingent upon the rotational speed of the cable disc within the winch system, as well as the diameter of the current winding layer of the tow cable or towline array.

The load tension is defined as the towing tension provided by the winch system to meet the demand of the fibre optic towline array working underwater. Preliminary findings, based on a simulation of different working conditions and sea trial data from analogous projects, indicate that the maximum load tension of the winch system should not be less than 5kN, with the redundant design based on 6kN. The maximum take-up speed and cable release is defined as the outermost towline array moving line speed under the maximum rotational speed

of the cable disc. In accordance with the prevailing work demands, the maximum take-up speed of the winch system is specified at a minimum of 1m/s, while the maximum release speed is also set at this rate. The take-up speed is contingent upon the rotational speed of the cable disc within the winch system, as well as the diameter of the current winding layer of the tow cable or towline array.

In accordance with the stipulated requirement for optimal cable take-up and release speed, the primary inverter motor, with a rated speed of 1500rpm, has been selected. The transmission system incorporates a helical-bevel gear reducer, exhibiting a reduction ratio of 62.55. It is evident that the cable disc speed is capable of attaining 23.98 rpm when the main motor's torque and speed are below the optimal levels.

From the formula:

$$V_n = \frac{s\pi D_n}{60}$$

Formula: s—rated speed;

D_n —Medium diameter of the nth layer of the cable;

V_n —Nominal linear velocity of the nth layer of the cable.

According to the winch take-up and payoff power needs, the system power unit adopts inverter motor + helical gear - spiral bevel gear reducer structure, the rated power of the motor is 11KW, the rated speed is 1500rpm, the reduction ratio is 62.55, and the output torque $M = 4560N.m$.

According to the above table, it can be seen that the maximum speed of the winch can be up to 1.58m/s, the maximum tension 12991N, to meet the maximum release speed $\geq 1m/s$, the maximum load tension $\geq 5kN$ total requirements.

2.5. Design Calculation and Strength Calibration of Cable Discharge Mechanisms

The system utilises two distinct specifications of towing cable, designated as 'φ18' and 'φ38'. The 'φ18' specification cable is positioned within the inner layer of the cable disc, while the 'φ38' specification cable is situated in the outer layer. Due to variations in cable diameter and the configuration of cable layers, the influence of the two cable types on line angle changes is significant. The specific forces exerted by the towing cable and towing array are illustrated in Fig. 3, respectively.

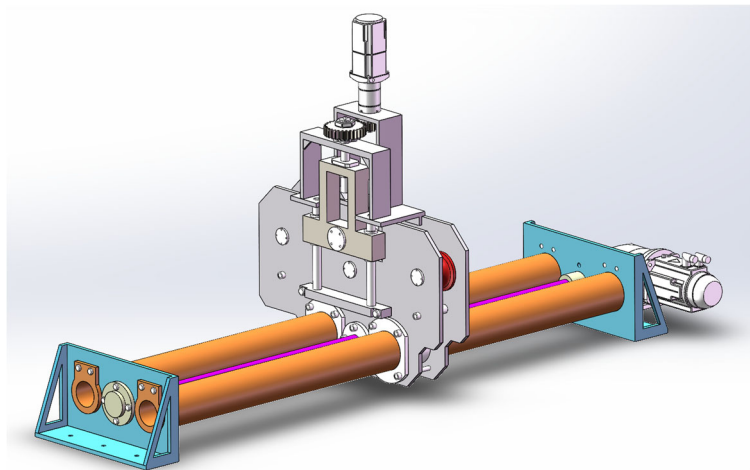


Figure 2. Modelling of cable routing units

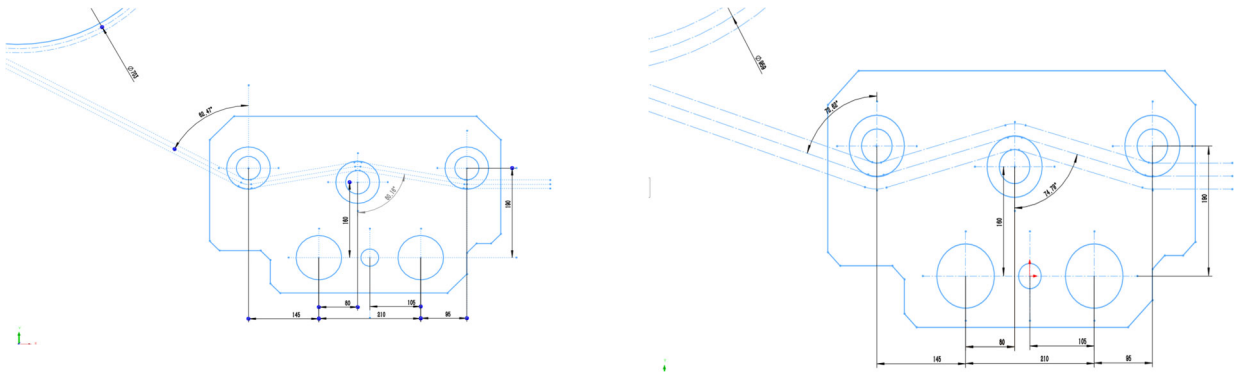


Figure 3. Different cable force diagrams

Upon thorough examination of the force condition depicted in the aforementioned diagrams, it is evident that the cable discharge mechanism's force is predominantly attributable to the positive pressure exerted by the cable on the guide pulley. The dimensions of the pulley are found to be predominantly contingent on the cable's maximum working tension (10 kN)

and the angle of force during the cable's discharge.

In the process of winding up the trailing cables with a diameter of either 18 or 38 mm, the cable unit's discharge is subjected to a distinct force.

To ensure the precision of the calculations, the cable diameters of both types are meticulously calculated.

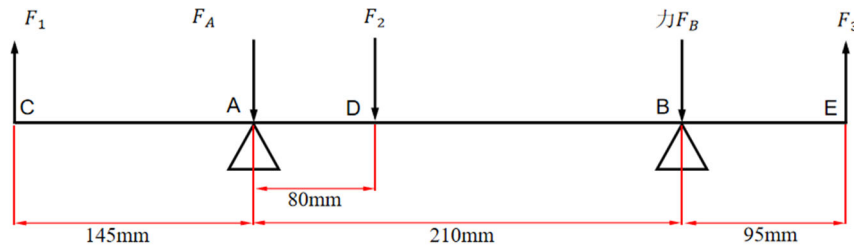


Figure 4. Force analysis diagram

Calculation of forces in 18mm cable rows:

$$\begin{cases} F_1 = 10^4 \times \cot 80.16^\circ + 10^4 \times \cot 62.47^\circ \\ F_2 = 2 \times 10^4 \times \cot 80.16^\circ \\ F_3 = 10^4 \times \cot 80.16^\circ \\ -F_1 \times l_{CA} - F_2 \times l_{AD} - F_B \times l_{AB} + F_3 \times l_{AE} = 0 \\ -F_1 \times l_{CB} + F_A \times l_{AB} + F_2 \times l_{DB} + F_3 \times l_{BE} = 0 \end{cases}$$

F is also the maximum force on the wire guide wheel in the process of arranging the wires, and the diameter of the wire guide wheel shaft and the selection of the wire guide wheel bearings are also designed according to this force.

Calculation of forces in 38mm Fiber-Optic Towed Array:

$$\begin{cases} F_1 = 10^4 \times \cot 74.78^\circ + 10^4 \times \cot 72.62^\circ \\ F_2 = 2 \times 10^4 \times \cot 74.78^\circ \\ F_3 = 10^4 \times \cot 74.78^\circ \\ -F_1 \times l_{CA} - F_2 \times l_{AD} - F_B \times l_{AB} + F_3 \times l_{AE} = 0 \\ -F_1 \times l_{CB} + F_A \times l_{AB} + F_2 \times l_{DB} + F_3 \times l_{BE} = 0 \end{cases}$$

The maximum value of the force on the guide shaft A is $F_{Amax} = 8811N$, The maximum value of the force on the guide shaft B is $F_{Bmax} = -3598N$.

3. Integrated Structural Design of the Marine Winch

3.1. Winch Design Specifications

Fig. 5 shows the simplified model of the winch drum and its meshing in ANSYS software. According to the complexity of the structure in different regions, a multi-scale meshing strategy was applied to the model, and three mesh sizes of 10 mm, 25 mm, and 50 mm were set to improve the computational efficiency and local accuracy of the simulation. In terms of material, Q345 is selected as the construction material of the cable storage winch reel to meet the strength and engineering application requirements.

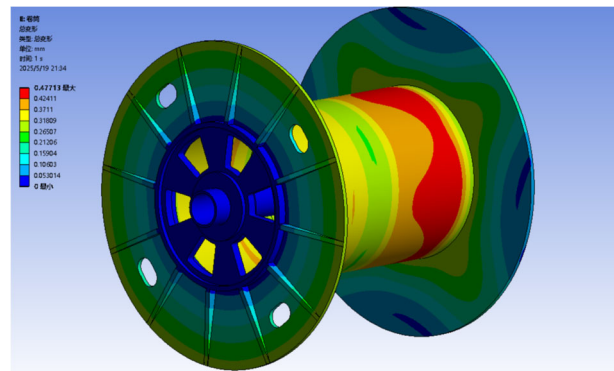
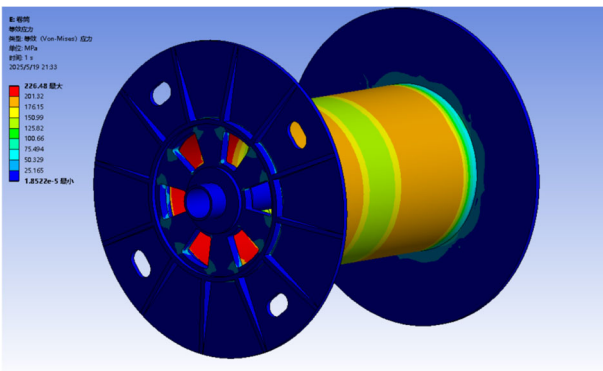


Figure 5. Stress and total deformation diagrams for reels

As demonstrated in Fig. 5 , the maximum stress on reel 226.48MPa is less than the yield limit of Q345, with a maximum deformation of 0.48 mm, which is smaller and within the permissible range. Furthermore, the maximum strain of 1.121e-003 is also within the permissible range. The system's results demonstrate that the structural strength and stiffness of the reel meet the design requirements, with adequate safety margins.

3.2. Finite element analysis of braking systems

In order to achieve the maximum 10kN braking capacity of

the system, a braking device driven by an electric actuator is provided under the cable disc side of the winch near the motor. The braking function of this device is activated during the high-speed towing array navigation of the mother ship. Specific operation process winch first deceleration, and automatically aligned with the brake hole on the side plate; then the motor brake start, at the same time, the electric actuator drive brake pin inserted into the conical hole on the side plate of the cable disc, and self-locking, complete the braking process, and ultimately rely on the brake pin to achieve mechanical locking.

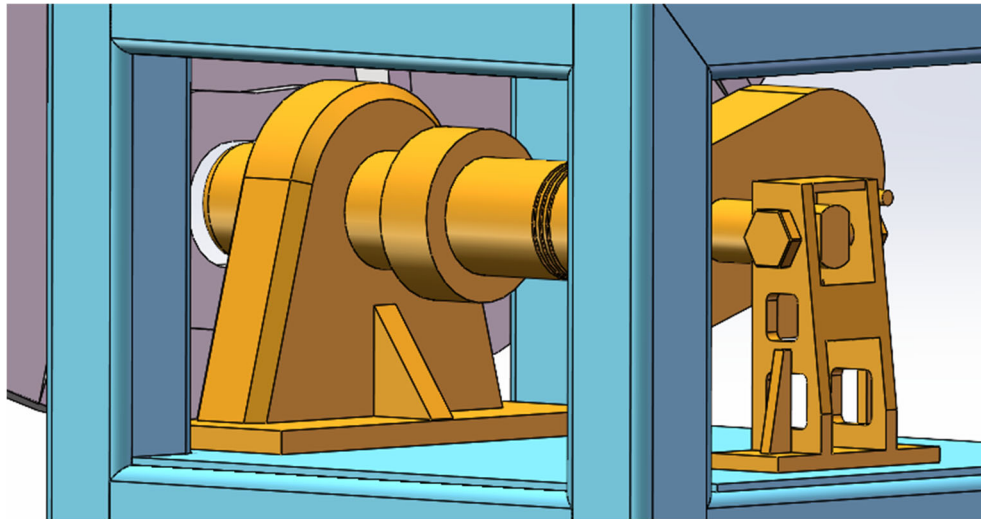


Figure 6. Brake unit model drawing

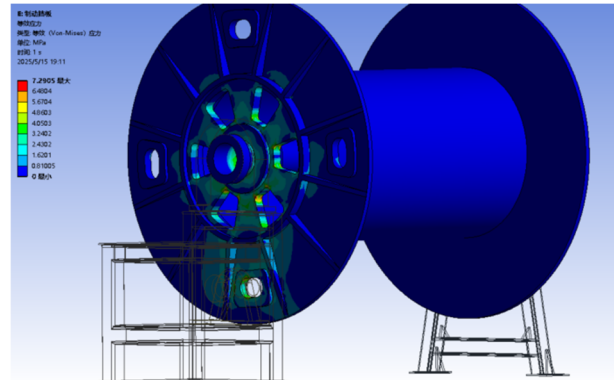
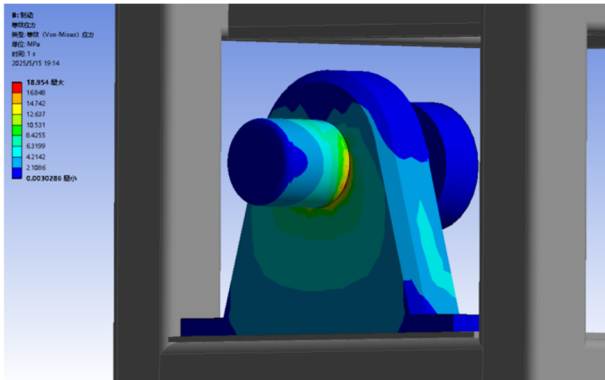


Figure 7. Maximum stress on the brake

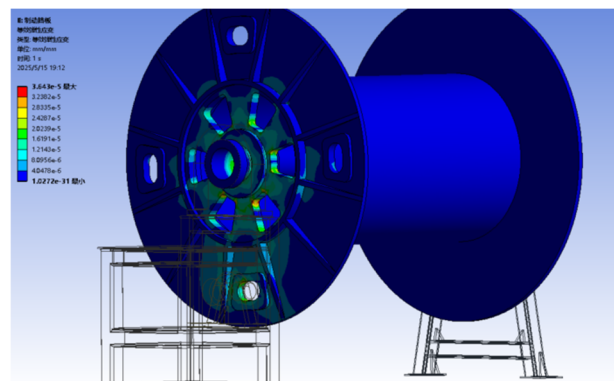
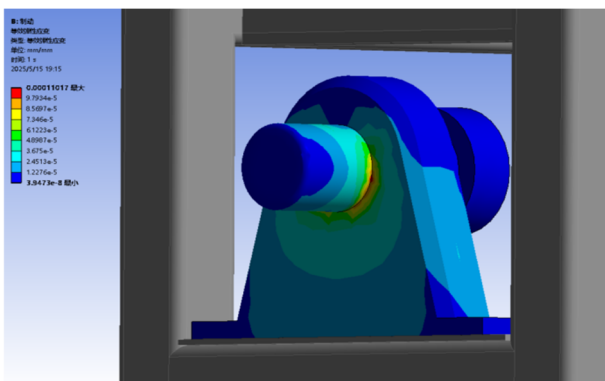


Figure 8. Maximum strain on the brake

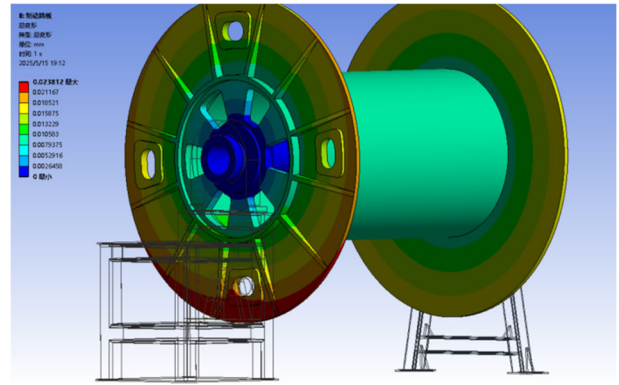
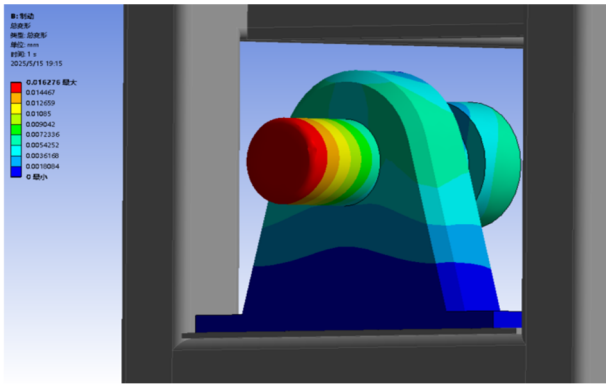


Figure 9. Maximum deformation of the braking device

In order to ascertain the cable receiving unit's requisite strength and stiffness, commensurate with the system's actual conditions, a mechanical simulation analysis was conducted. This analysis encompassed the cable receiving unit's primary simulation conditions within the system, encompassing an abnormal state of tension, a 10kN braking event, and the cable receiving unit's capacity to withstand these conditions. The specific simulation outcomes are delineated in Fig. 7 8 9. As illustrated in Fig. 7 8 9, the maximum stress on the brake pin is 18.9MPa less than the yield limit of the high-quality steel material. The maximum deformation is 0.016mm, which is smaller and within the permissible range. The maximum strain is 1.1101e-004 in the permissible range. The maximum stress on the cable disc during braking is 7MPa. It is evident that the material's yield limit for Q345 is 29MPa, and the maximum deformation recorded was 0.024mm. This is smaller than the yield limit and falls within the permissible range. Similarly, the maximum strain of 3.643e-005 is within the permissible range, thereby meeting the stipulated strength and stiffness requirements. To summarise, the findings indicate that when exposed to the maximum braking force, the cable take-up unit's structural strength and stiffness align with the design specifications, exhibiting a substantial safety margin.

4. Conclusion

The initial section of this paper is devoted to a comprehensive description of the winch's partial structure and the underlying working principle. Secondly, the main parameters of the traction winch are designed according to the requirements of the winch itself. Furthermore, the mechanical model of the winch drum, braking and cable discharge system

has been established. The strength of these components is analysed by stress analysis, and then compared with the permissible stress of the selected materials. This process verifies that the strength of the important components meets the design requirements.

The findings of this study provide a foundation for future research in this area.

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