The Finite Element Simulation Analysis and Modeling Method of the Influence of Cable Pretension Force on the Vibration of Marine Winches

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Abstract. Marine winches are prone to vibration issues in dynamic marine environments due to the mechanical behavior of cables, which can affect the stability and safety of the equipment. This study, based on finite element simulation technology, proposes a refined modeling method for the cable-winching system. It employs cable elements (Cable280 elements) to simulate the large deformation and nonlinear mechanical behavior of cables. By combining static and harmonic response analyses, the research systematically investigates the dynamic response characteristics of winch vibrations under different pre-tension force conditions. The findings reveal that flexible cables can experience displacement reaching 10%-20% of their length under load, necessitating large deformation analysis. Stress is concentrated on the drum and distributed in an annular pattern. Harmonic response analysis indicates that pre-stress significantly influences high-frequency vibrations (6000-8000Hz), and the mechanism by which pre-tension force affects vibration characteristics is analyzed. The research results provide theoretical basis and technical support for the structural optimization, vibration suppression, and pre-tension parameter design of marine winches.

Keywords: Cable pretension force; Marine winch; Finite element simulation; Cable element; Harmonic response analysis; Vibration characteristics.

1. Introduction

Marine winches, as crucial equipment in ships and marine engineering, are widely used in anchor handling, towing operations, and other scenarios. Their performance and reliability directly impact operational safety and efficiency. In dynamic marine environments, winches often experience vibration issues due to the complex mechanical behaviors of cables. Such vibrations not only affect equipment stability but can also lead to structural fatigue and failure. Therefore, an in-depth investigation into cable mechanical characteristics and their coupling mechanisms with winch vibrations is of great significance for optimizing winch design and enhancing operational safety.

Scholars both domestically and internationally have conducted research on cable modeling and dynamic characteristics: In 2002, ELLIOTT addressed the deficiency in cable modeling by treating cables as flexible elements with variable stiffness/mass and tension-only properties, establishing a pulley-rope model and applying it to the analysis of aircraft carrier arresting gear [1]. In 2011, Kwang-Phil Park simplified the drum mechanism and considered dynamic coefficients to analyze the dynamic response of quay cranes, investigating the effects of rope reeling speed and acceleration time on smoothness [2]. Wiescel and Hartland designed a multi-layer winding structure to assist wire rope layer changing, but their work lacked theoretical depth and did not validate high-speed cable reeling [3]. In 2013, Dong Dashan et al. compared three methods—flexible rod substitution, point mass modeling, and sleeve force analysis—emphasizing the importance of tension variation in modeling, providing references for ADAMS modeling [4]. In 2017, Hu Jingbo et al. utilized ADAMS to analyze the cable reeling process of a 34t crane's Lebus drum, obtaining wire rope force characteristics [5]. The same year, Kevac studied rope winding dynamics, analyzing the variation regularity of cable-drum contact forces during same-layer winding, offering valuable references for marine winch design optimization [6].

Current research primarily focuses on static mechanical analysis of winch structures or response prediction under single loads, with insufficient attention paid to the dynamic correlation between cable pretension force and vibration characteristics. Traditional modeling methods such as beam elements or rod elements struggle to accurately simulate cable large deformation, nonlinear contact, and pretension effects, leading to discrepancies between simulation results and actual operating conditions. Additionally, the mechanism by which pretension force influences the harmonic response of winch systems remains unclear, lacking systematic quantitative analysis.

This study is based on finite element simulation technology and proposes a refined modeling method for cable-tackle systems. It utilizes the Cable280 unit to simulate the large deformation and nonlinear mechanical behavior of cables. By combining statics and harmonic response analysis, it systematically investigates the dynamic response characteristics of winch vibration under different pretension conditions. Through comparing the stress distribution, displacement characteristics, and frequency-amplitude curves under different tensions, the mechanism by which pretension affects system stiffness, modal frequencies, and vibration amplitudes is revealed. The research results provide theoretical basis and technical support for the structural optimization, vibration suppression strategy formulation, and preload parameter design of marine winches, contributing to the efficient and reliable operation of marine engineering equipment.

2. Cable Finite Element Modeling Method

2.1 Introduction to Cable Element

Cable structures are lightweight and prone to large displacements, requiring specialized elements to accurately simulate their responses. The Cable280 element, a special Link180 rod element designed for unidirectional tension only, employs higher-order shape functions to achieve better convergence characteristics than the Link180. This element comprises four nodes (I, J, K, L), with node L serving as a directional point, which can often be neglected since the focus is primarily on axial force and area[7]. The geometry of the element is illustrated in Fig. 1.

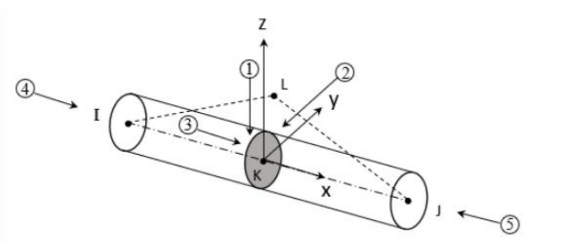


Fig. 1 Cable280 element model

The Cable280 unit has significant advantages over traditional bar/beam units, primarily in the following aspects:

(1) **Geometric Nonlinearity Handling**: Traditional beam units assume uniform stiffness, making them unsuitable for large deformations. In contrast, the Cable280 unit can accurately simulate tensile stiffness and deformation/stress distribution along its length, making it suitable for large deformations, bending, and coupled axial tension-shear conditions.

(2) **Support for Complex Loads**: It supports contact analysis, friction, and slip, enabling flexible dynamic/time history analysis.

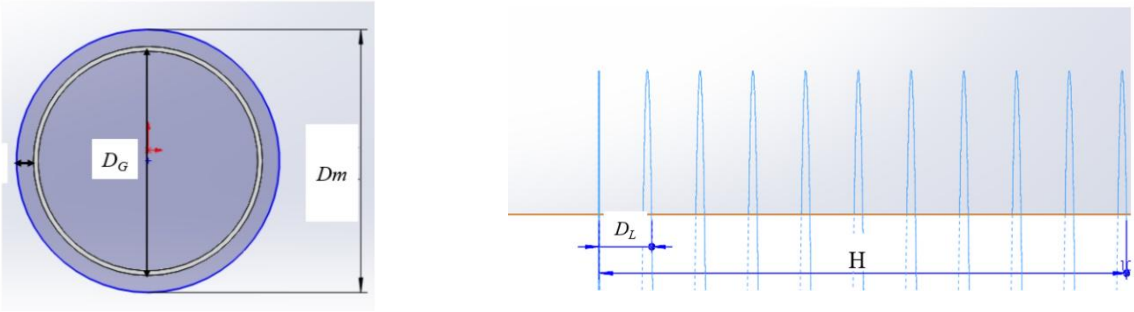
(3) **Modeling Precision**: It provides a more accurate representation of complex mechanical characteristics for structures such as cables and bridges, enhancing the reliability of the analysis.

2.2 Cable Conversion to Line Elements

Before performing cable modeling, first determine the cable diameter D_L and drum diameter D_G. The specific diameter D_m of the cable array base circle is determined jointly by the cable diameter and drum diameter, as shown in Fig.2-(a), with the specific calculation formula as follows:

$$D_m=D_G+D_L\ . \tag{1}$$

The method accurately represents the actual configuration, with the cable array tightly wound around the drum. Note that the pitch is defined as the spacing between each turn of the cable in the array. Based on the actual cable distribution, the spacing between each turn is 0, so the pitch equals the cable diameter D_L. The height corresponds to the cable array length H, and the spiral of the cable array is shown in Fig.2-(b).



(a) Cable modeling dimensional schematic diagram (b) Cable array helix dimensionalschematic diagram

Fig. 2 Cable solid modeling

2.3 Cable Line Conversion

In Section 2.1, the cable array solid modeling has been completed, and the non-flexible bodies need to be converted into line elements using finite element software, as shown in Fig. 3-(b). The line body model facilitates the application of boundary conditions and loads, enabling efficient computations and avoiding memory overflow and time-consuming issues in large-scale structural analysis. The generation of line bodies essentially involves extracting the spline curves of the cables and assigning cross-sectional information.

In finite element software, line bodies are defined as cable elements, and the Cable unit is used for meshing to ensure that the deformation behavior of the line bodies aligns with the characteristics of real flexible cables, as illustrated in Fig. 3-(b). Cable material is defined as polyurethane.

(a) Cable line (b) Cable mesh element

Fig. 3 Cable Line Conversion

2.4 Modeling of Cable and Drum Connection

In subsequent simulation calculations, it is necessary to define the friction between the rope and drum, the friction between ropes, and the endpoint binding forms. Among these, the contact between the rope and drum is critical. In reality, the two come into direct contact, but solid modeling may lead to penetration issues.Therefore, during initial modeling, the rope and drum should maintain an initial gap. The gap is determined based on the cable diameter DL and should be kept below 0.4DL to avoid calculation errors.

The connection between the cable endpoints and the drum employs rigid constraints. In the finite element model, this is achieved through rigid contact between the cable element (Cable280) and the solid element (Solid185). After isolating the contact structure for display, the final cable model is established as shown in Fig. 4.

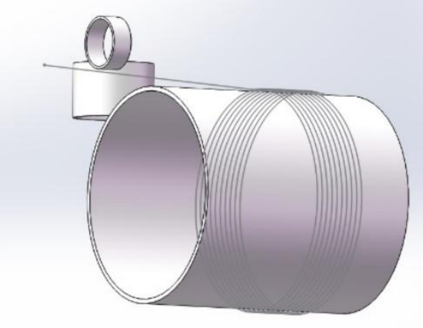


Fig. 4 Modeling of cable anddrum connection

3. Analysis of the Influence of Cable Pretension Force on Vibration

To accurately obtain the vibration response of the winch under different cable tension conditions, a simulation analysis of the cable's effect on the winch structure's vibration response is conducted. A finite element model is established, and vibration response simulations under different operating conditions are performed and compared. Through static analysis, the stress changes in the cable under different operating conditions are examined, and the results are used as initial conditions for harmonic response analysis. The vibration responses under the same excitation but different operating conditions are then compared.

3.1 Static Mechanical Simulation Analysis of Cable Pre-tensioning State

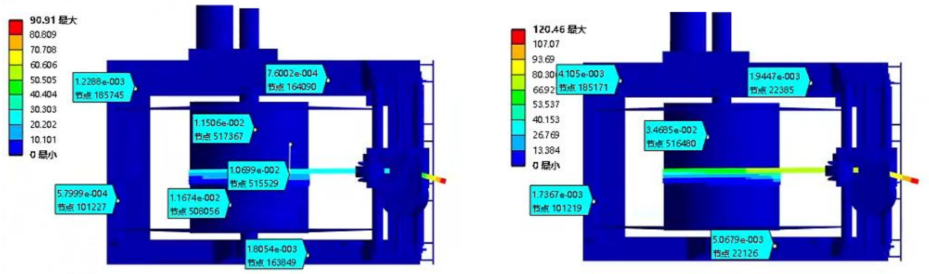
For cable analysis under different tensions, initial prestress is obtained by applying different tensile forces. As shown in Fig. 5-(a), tensile forces of 1000N, 3000N, 6000N, and 9000N are applied at the cable head, with the tail end fixed. After exiting the cable laying mechanism, the cable generally has an inclination angle, set at 15°, and the lateral tensile force is determined using the sine and cosine laws. The cable deformation, as shown in Fig. 5-(b), is as expected. Tensile force transmission requires a process, so the displacement of the cable away from the force application point is small, while the displacement near the force application point is large. The tail end is fixed, and the displacement of the cable near the tail can be negligible.

Figure 6 shows the deformation under different tensile forces, indicating that as the tensile force increases, the cable elongation increases, with deformation primarily resulting from the elongation of the cable body under traction force. Deformation at other locations of the winch is small, and their displacements are negligible compared to the cable elongation. Under ultimate load, the cable displacement reaches 241.05mm (cable length 1700mm, displacement accounting for 14.2% of the cable length). Since the displacement reaches 10%-20% of the cable's initial length, it is typically considered "large deformation," requiring large deformation analysis.

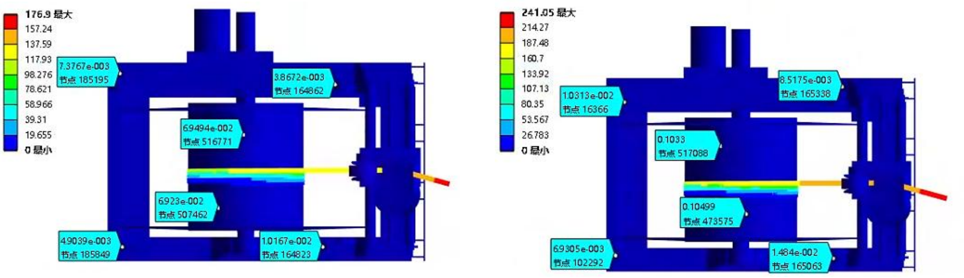
Fig. 7-(a) shows the stress distribution under a pre-tension force of 6000N. The stress response of the winch as a whole and the drum is primarily caused by the friction between the cable and the drum during the tensioning process. The stress is concentrated on the drum, with significantly lower stress levels at other locations. Figure 7-(b) indicates that the drum stress exhibits a circumferential ring-shaped distribution, consistent with the cable winding method, resulting from the force transmission during cable tensioning

(a) Tension application position (b) Cable deformation result

Fig. 5 Tension application position and cable deformation result

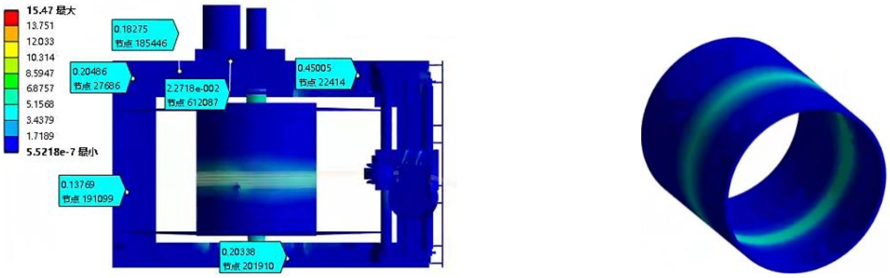


(a) 1000N (b) 3000N



(c) 6000N (d) 9000N

Fig. 6 Tension application position and cable deformation result



(a) Overall stress distribution of the winch (b) Stress distribution of the drum

Fig. 7 Stress distribution under 6000N pre-tension force

3.2 Cable Pre-tension State Harmonic Response Simulation Analysis

After the static analysis is completed, the cable has a certain preload, and the overall structure generates partial stress due to the tensioning of the rope. The results of the static analysis are used as the initial conditions for vibration analysis, and harmonic response analysis is employed to study the vibration response.

The winch is connected to the mother ship via mounting feet, and the focus is on the vibration impact of cable movement on the mounting feet positions. The bottom four fixed mounting feet are selected as the target response points. The excitation source originates from the motor and gearbox, with a nodal force of 100N applied vertically at the gearbox location. The frequency scan range is set from 0 to 8000Hz. The amplitude curves of the response points within the 0-8000Hz range are shown in Fig. 8.It can be observed that the preload has a more significant effect on high-frequency vibrations, while at low frequencies, the amplitudes for all conditions are relatively small. The influence becomes more apparent as the frequency increases, particularly within the 6000-8000Hz range. The amplitude curves under different tensions show that within the 0-8000Hz range, amplitude curves of response points with tension show significant differences compared to the initial state without prestress, indicating that cable tension affects the structural vibration response.

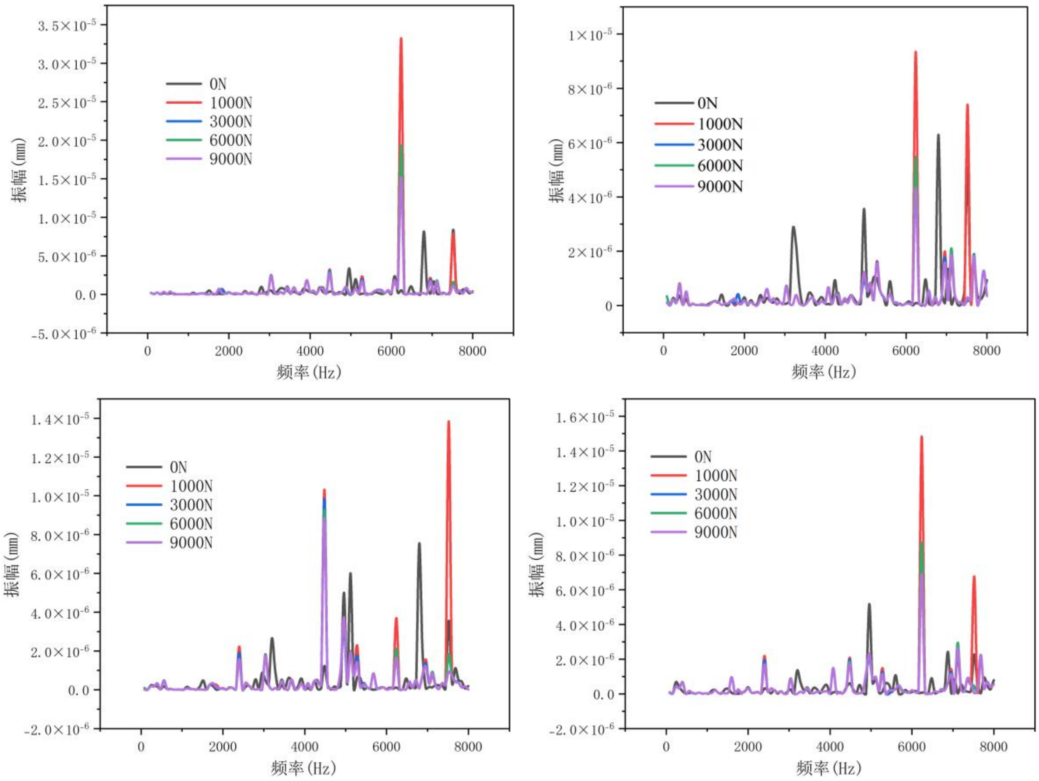


Fig. 8 Amplitude curves at four machine feet response points

3.3 Analysis of the Principle of Cable Pretension Force on Vibration

The mechanism by which different pre-tension forces of the cable affect the overall vibration characteristics of the marine winch can be summarized in four aspects:

(1) Changes in Structural Stiffness and Natural Frequency

Material mechanical properties: An increase in pre-tension force enhances structural stiffness, particularly for nonlinear materials such as cables, directly leading to an increase in system natural frequency. Under the same excitation conditions, vibration amplitude is significantly altered due to frequency deviation.

Geometric nonlinear effects: Large tension-induced geometric deformation alters stiffness distribution. For example, cable axial elongation under tension (with displacement reaching 14.2% of initial length under extreme working conditions) causes local stiffness variations, thereby affecting the shift of amplitude-frequency curves in harmonic responses.

(2) Vibration Modes and Coupling Effects

Modal shape transformation: As tension increases, low-order bending modes gradually transition to tensile or combined tension-bending modes. For instance, cable vibration under tension shifts from localized bending to overall tensile vibration, suppressing energy accumulation in the resonance frequency range.

Modal coupling effects: High tension may induce coupling between different vibration modes (e.g., bending and tensile modes), complicating system harmonic response characteristics, with pre-stress having a more pronounced effect on high-frequency vibrations.

(3) Contact Friction and Damping Characteristics

Dynamic adjustment of friction interfaces: Changes in tension alter contact pressure and friction coefficients between the cable and drum or between cables, thereby influencing vibration energy dissipation. For example, stress concentration in drum contact areas under high tension enhances frictional energy dissipation, suppressing low-frequency vibration amplitudes.

Correlation of damping characteristics: Pre-tension indirectly affects material internal damping by altering deformation extent. For instance, large deformations may cause nonlinear changes in viscoelastic material damping characteristics, further modulating harmonic response amplitudes.

(4) Boundary Conditions and Constraint States

Boundary deformation effects: Tension applied to non-fixed structures may cause minor displacements at support points (e.g., suspension systems), thereby changing system boundary constraints and inducing significant fluctuations in vibration responses.

Reconstruction of contact constraints: Structural deformation caused by tension may trigger new contact or constraint states. For example, local slippage during cable winding alters dynamic contact force distribution, directly impacting system dynamic responses.

Pre-tension force comprehensively influences vibration characteristics through multiple mechanisms, including stiffness regulation, modal coupling, frictional energy dissipation, and boundary reconstruction. Low-frequency vibration suppression relies on increased stiffness and frictional energy dissipation, while differences in high-frequency responses originate from modal coupling and geometric nonlinear effects. These findings provide a theoretical foundation for frequency-specific optimization strategies in vibration control under complex operating conditions.

4. Summary

Marine winches are prone to vibration issues in dynamic ocean environments due to the mechanical behavior of cables, which can affect the stability and safety of the equipment. This study employs finite element simulation technology, utilizing cable elements (Cable280 units) to establish a refined model of the cable-winch system. By integrating static and harmonic response analyses, the research investigates the dynamic response patterns of the winch under different cable pretension conditions.

Static analysis reveals that flexible cables made of polyurethane can experience displacements of 10%–20% of their length under load, necessitating large deformation analysis. Stress concentrations are observed around the drum, distributed in a ring pattern. Harmonic response analysis indicates that pretension significantly influences high-frequency vibrations (6000–8000 Hz). As pretension increases, system stiffness improves, leading to an upward shift in natural frequencies. Modal transitions occur from low-order bending to stretching/bending modes, while contact friction energy dissipation enhances, thereby suppressing high-frequency vibration amplitudes. The study elucidates how pretension affects vibration characteristics through mechanisms such as stiffness modulation, modal coupling, contact friction, and boundary condition reconstruction.

The findings provide theoretical support and technical guidance for marine winch structural optimization, vibration suppression strategy development, and pretension parameter design. They offer valuable insights for enhancing the reliability and safety of marine engineering equipment under complex operational conditions.

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