

Static and Modal Analysis of a Coil Needle Structure

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Abstract

This paper mainly conducts static and dynamic mechanical analysis of the coil needle structure in the battery cell winding machine device. As the coil needle structure directly supports the battery cell and performs the cell winding process, the rationality and stability of its design directly affect the accuracy of cell winding formation. Therefore, static and modal analysis of the coil needle mechanism is carried out to verify its static and dynamic mechanical performance under working conditions.

Keywords

Battery Cell Winding Machine; Coil Needle Structure; Static Analysis; Modal Analysis; Mechanical Performance.

1. Introduction

With the rapid development of new energy vehicles and energy storage systems, there are higher requirements for the performance and quality of lithium-ion batteries as crucial energy storage devices [1]. In the battery manufacturing process, the winding equipment plays a vital role, with the winding needle structure being its core component. The statics and vibration characteristics of the winding needle mechanism have a critical impact on the equipment's performance [2-3]. Through static analysis, the force distribution of the winding needle mechanism can be studied to optimize its structure, improve its load-bearing capacity and stability, and ensure the reliability of the equipment during high-speed and high-precision operation [4-6]. Modal analysis, on the other hand, helps determine the inherent vibration frequencies of the structure, avoiding vibration issues caused by resonance and enhancing the operational stability and safety of the equipment [7-10]. Modal analysis also provides a basis for optimization design, improving the vibration characteristics of the winding needle mechanism, and consequently enhancing the equipment's performance and reliability. This study aims to comprehensively investigate the force distribution and vibration characteristics of the winding needle mechanism by combining static and modal analysis methods, providing comprehensive support for the design and manufacturing of battery winding equipment. By conducting static and modal analysis of the winding needle mechanism, this research offers theoretical guidance and practical support for the stable operation and efficient production of related equipment. Additionally, this study contributes to the technological advancement of China's new energy industry, fostering the development of the country's new energy sector.

2. Theoretical Foundations of Finite Element Simulation Analysis

The finite element method is a technique that combines computational mathematics and elasticity theory, using numerical analysis through computer software. It plays an important role in solving problems in practical engineering projects. Finite element analysis can provide

mechanical performance information for various engineering structures and simulate the rationality and reliability of structural engineering designs. To achieve this goal, this paper utilizes ANSYS Workbench finite element simulation software for static and dynamic mechanical analysis.

According to classical mechanics theory, it can be understood that in classical mechanics, based on Newton's second law, the general expression of ANSYS Workbench for structural dynamics equilibrium equation is:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(t)\} \tag{1}$$

$[M]$ —Mass matrix

$[C]$ —Damping matrix

$[K]$ —Stiffness matrix

$\{x\}$ —Displacement vector

$\{F(t)\}$ —Force vector

$\{\dot{x}\}$ —Velocity vector

$\{\ddot{x}\}$ —Acceleration vector

In dynamic analysis involving impact collisions and rapid loading, it is essential to consider the effects of damping and inertial forces. When analyzing structures under static conditions or relatively slow loading velocities, dynamic analysis calculations can be approximated to the results obtained from static analysis. In linear static analysis, where the analysis results are not influenced by time factors, the mechanical equilibrium equation can be simplified by neglecting time-dependent variables.

$$[K]\{x\} = F \tag{2}$$

Modal analysis [11] is the most fundamental dynamic analysis and is a numerical technique used for analyzing the vibration characteristics of structures. It serves as the basis for other dynamic analyses. Conducting modal analysis during practical product design can determine the natural frequency and characteristics of its vibration, which can effectively avoid damage to the structure caused by resonance phenomena. In general modal analysis, no external excitation load is applied, and the effect of damping is neglected. Therefore, Equation (1) can be simplified as follows:

$$[M]\{\ddot{x}\} + [K]\{x\} = 0 \tag{3}$$

For linear systems, their free vibration is characterized by simple harmonic motion, which can be expressed as follows:

$$\{x\} = \{\phi\}_i \cos \omega_i t \tag{4}$$

$\{\phi\}_i$: The characteristic vector of the vibration mode corresponding to the i-th order; ω_i : The natural frequency (in rad/s) of the i-th order mode.; t : time (unit: s).

By substituting equation (4) into equation (3), the motion equation can be simplified as follows:

$$([K] - \omega_i^2 [M])\{\phi\}_i = 0 \tag{5}$$

When the structure is undergoing free vibration, the nodal amplitudes $\{\phi\}_i$ are all non-zero. Therefore, the coefficient determinant in equation (5) is equal to zero, i.e:

$$\det[K] - \omega_i^2[M] = 0 \tag{6}$$

3. Static Analysis of Coil Spring Structure

3.1. Establishment of Coil Spring Structure Model

When establishing simulation models in ANSYS Workbench, the geometric model can be created either using its own DesignModeler module or by using other 3D modeling software. The geometric model can then be seamlessly connected to ANSYS Workbench or saved as a Parasolid (.x_t) format for external import as a neutral file to establish the geometric analysis model. The geometric model of the coil spring mechanism in this paper was created using Solidworks and then imported into ANSYS Workbench using the Parasolid (.x_t) format files saved from Solidworks. Due to the complexity of the actual connection relationships and small fillets in the coil spring mechanism model, it can affect the simulation solution speed and increase the difficulty of solving in finite element analysis. In order to effectively conduct simulation analysis and facilitate the observation of analysis results, the model was simplified by adding the simplified model parts as constraints or loads. The simplified model is shown in Figure 1.

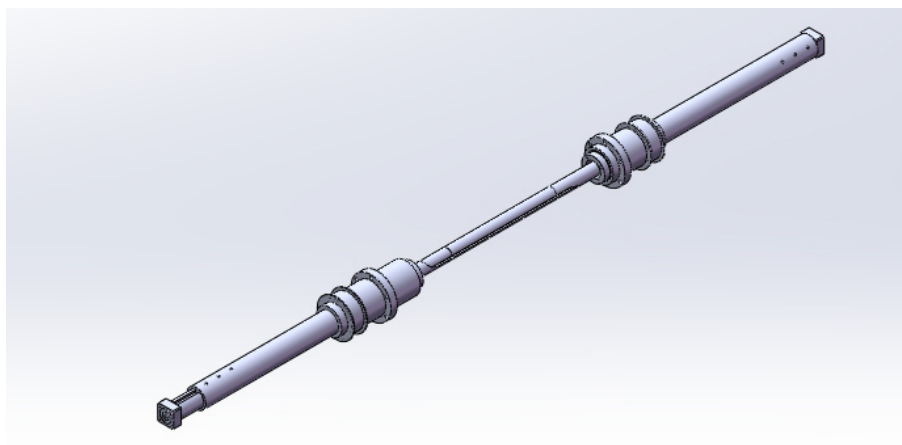


Fig 1. Schematic Diagram of the Simplified Coil Spring Mechanism Model

3.2. Definition of Material Properties

In the design of the coil spring structure, it is essential to ensure that the overall structure has sufficient rigidity after winding the core, while also aiming for lightweight and compact coil spring mechanism. The primary material selected for this mechanism is Q235 carbon structural steel, chosen for its excellent plasticity, high strength, good thermal workability, and high toughness. By consulting relevant material mechanics performance tables, it is found that the density, elastic modulus, and Poisson's ratio parameters of Q235 structural steel are as shown in Table 1.

Table 1. Battery cell related parameters

Material	Density(kg/m ³)	Elastic Modulus(GPa)	Poisson's Ratio
Q235 Structural Steel	7.85x10 ³	210	0.3

3.3. Mesh Partitioning

The main idea of finite element simulation analysis is to divide the overall simulation model into a finite number of small elements for analysis and calculation. Therefore, mesh partitioning is an important step in performing finite element simulation analysis, and the quality of the mesh determines the quality of the elements. Common methods for finite element mesh partitioning in ANSYS Workbench include tetrahedral mesh, hexahedral mesh, swept mesh, and multi-zone partitioning mesh methods. Since the components in the coil spring structure model are relatively regular, tetrahedral meshing is mainly used for mesh partitioning. Due to the varying sizes of model components, sizing is used to refine the mesh partitioning for each part. In this model, the mesh elements are classified and refined according to the sizes of the model components, with main mesh element sizes of 10mm, 3mm, and 0.5mm. The overall model after partitioning is shown in Figure 2. After mesh partitioning, the model is divided into a total of 49,683 elements with 163,999 nodes.

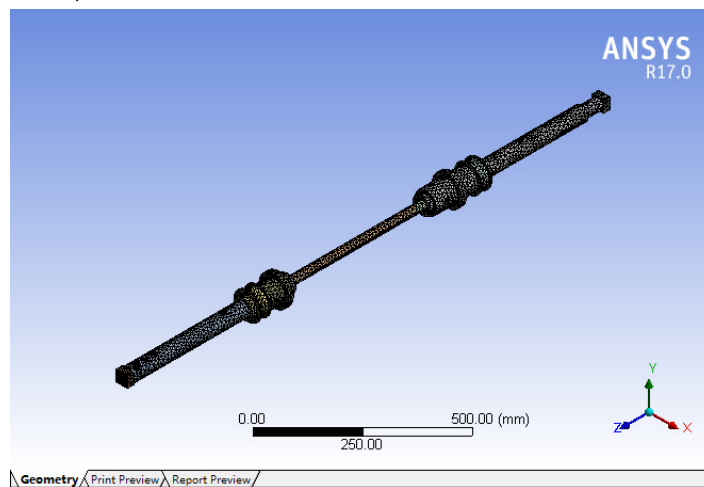


Fig 2. The mesh partitioning model of the coil winding mechanism

3.4. Apply Boundary Loads

Based on the working conditions of the coil winding mechanism during the winding of large battery cell cores, corresponding boundary conditions are applied to the coil winding structure. Fixed constraints are added to the bolt holes of the left and right coil bearing seats and the left and right yarn guide connecting blocks. A torque load of 9500 N·mm is applied to the driving synchronous wheels on both sides, and a mass of 10 kg, equivalent to a force of 98 N, is applied to the coil as if it were winding a completed large battery cell core. The load situation of the coil winding structure is shown in Figure 3.

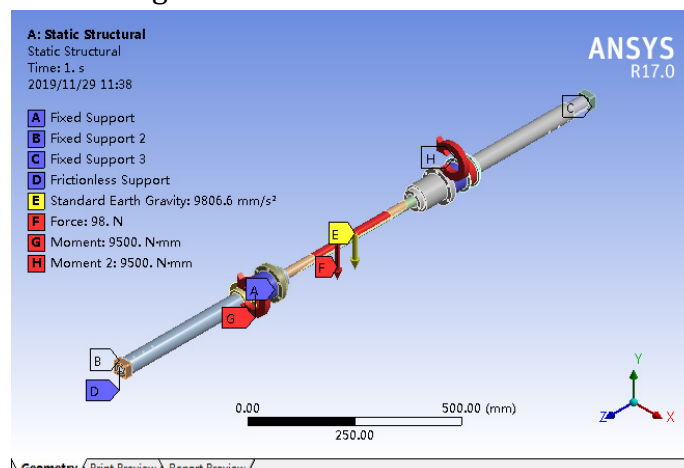


Fig 3. Schematic of Boundary Loads Applied to the Coil Winding Mechanism

3.5. Apply Boundary Loads

After the needle coil model undergoes operations such as model simplification, material property definition, mesh partitioning, and application of boundary loads, in the solution module of ANSYS Workbench, Total Information and Equivalent Stress are added. Then, by clicking on solve, the ANSYS Workbench finite element solver calculates the total deformation displacement cloud diagram for the needle coil structure static mechanical simulation analysis, as shown in Figure 4, and the equivalent stress cloud diagram, as shown in Figure 5.

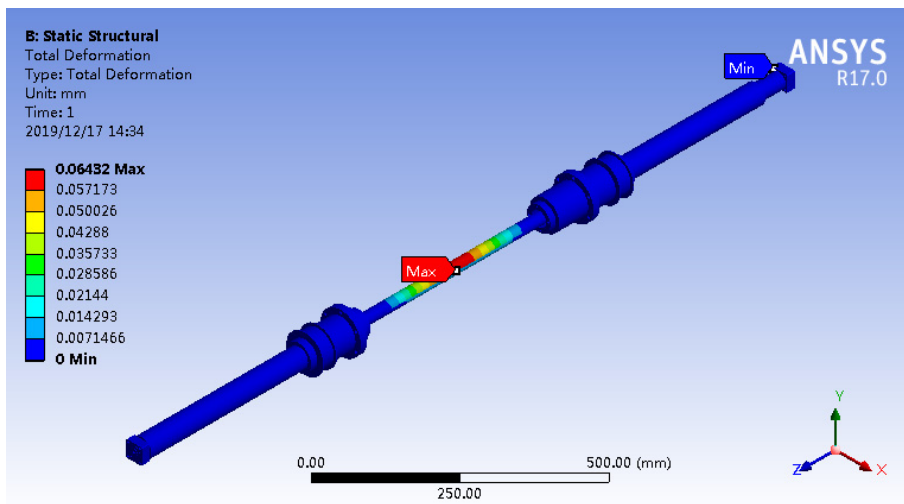


Fig 4. Total deformation displacement cloud diagram

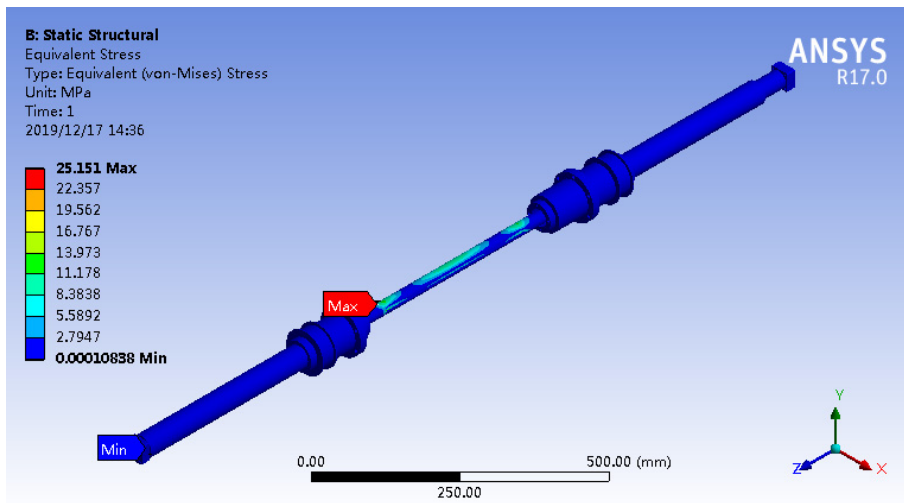


Fig 5. Equivalent stress cloud diagram

Based on the total deformation displacement cloud diagram and the equivalent stress cloud diagram, it can be inferred that the position experiencing the most significant deformation within the coil mechanism is located on the coil axis under a loaded load, with a maximum displacement deformation of 0.06432mm. While this meets the requirements for structural displacement deformation, in the actual process of winding large battery cell cores, various errors such as manufacturing errors, assembly errors, and measurement errors may exist in the equipment. The accumulation of these errors can affect the accuracy of cell formation. Therefore, further optimization of the coil structure is necessary to reduce its maximum deformation under the load of cell formation, thereby improving the quality of cell winding production. From the equivalent stress cloud diagram, it is evident that the maximum stress primarily concentrates on the coil, with a maximum stress of 25.151 MPa, which is lower than

the allowable stress of 235 MPa for structural steel Q235. Hence, the structural resistance to failure is sufficiently large, meeting the design requirements.

4. Static Analysis of Coil Spring Structure

Modal analysis is the foundation for dynamic simulation analysis. Through modal analysis, mechanical structures can acquire their inherent frequency characteristics. Based on these frequency characteristics, potential resonance phenomena can be effectively avoided during structural design. Therefore, this study conducts modal analysis on the coil structure to determine its vibration characteristics. This analysis helps diagnose whether resonance phenomena might occur and verifies the modal properties of the coil structure. Modal simulation analysis is performed using the Modal module in ANSYS Workbench simulation software. A simplified finite element model of the coil structure is imported, and operations such as material property definition, contact definition, mesh partitioning, application of boundary constraints, and setting of the system modal solution order to 6 are conducted. Subsequently, modal solution calculations are performed to obtain the vibration characteristics of the coil structure's first six natural frequencies. The variations in the first six vibration natural frequencies and mode shapes are shown in Table 2 and Figure 6, respectively.

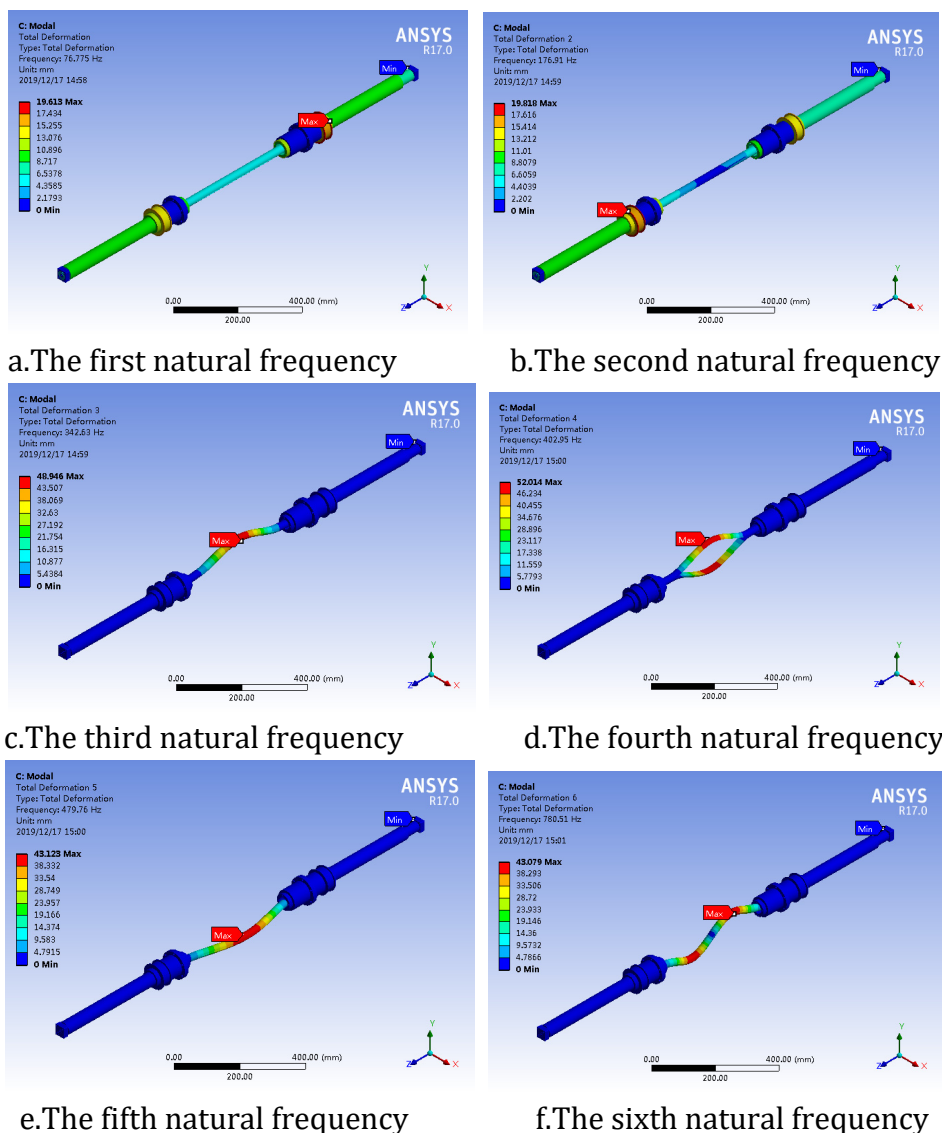


Fig 6. The first six mode shapes of the coil structure's natural frequencies

Table 2. The first six natural frequencies and mode shapes of the coil structure

Modal order	Frequency(Hz)	Mode shape
1	76.775	The overall mechanism experiences torsional vibration along the Z-axis
2	176.97	The overall structure undergoes torsional vibration along the Z-axis
3	342.63	The coil structure swings along the Y-axis
4	402.95	The coil structure swings up and down along the Y-axis
5	479.76	The coil winding structure swings along the X and Y axes
6	780.51	The coil swings along the X and Y axes

The mode shapes of the first six natural frequencies of the coil structure show that the natural frequency values range between 76.775Hz and 780.51Hz. In the first mode shape of the coil structure, the overall structure undergoes torsional vibration along the Z-axis; in the second mode shape, the overall structure also undergoes torsional vibration along the Z-axis; in the third mode shape, the coil swings along the Y-axis; in the fourth mode shape, the coil swings up and down along the Y-axis; in the fifth mode shape, the coil swings along the X and Y axes; and in the sixth mode shape, the coil swings along the X and Y axes. The main source of vibration in the coil structure comes from the vibration frequency of the servo motor. When the coil structure is winding the core at its highest speed, the servo motor rotates at 2000r/min. According to the relationship between frequency and speed given by ($n = 60f$), the frequency of the servo motor is calculated to be 33.3Hz. The first natural frequency of the coil winding mechanism is 76.775Hz, which is lower than the frequency of the servo motor at its highest speed, thus avoiding resonance phenomena.

5. Conclusion

This study comprehensively investigates the significant role of the coil winding mechanism in the manufacturing of batteries for new energy vehicles through in-depth statics and modal analysis. The static analysis reveals the force distribution of the coil winding mechanism under working conditions, providing crucial insights for the rational design of the structure. Meanwhile, modal analysis evaluates the stability and vibration characteristics of the coil winding structure. These findings offer new insights and methodologies for the design and manufacturing of relevant battery manufacturing equipment, contributing technical support to the promotion and application of clean energy technology.

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