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Practice-Oriented Teaching Research on Robot Statics Calculation and Simulation Course in Emerging Engineering Context

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Abstract: Based on the talent training requirements of the Robotics Engineering major under the Emerging Engineering Education initiative, the paper carries out a teaching reform for the 64-hour course Robot Statics Calculation and Simulation (32 hours for theory and 32 hours for practice), targeting prominent problems including abstract mechanical theories, disconnection between theoretical knowledge and practical operation, and non-hierarchical practical cases. In theoretical teaching, elasticity mechanics and Abaqus tutorials are integrated to align finite element knowledge with mechanical theories. For practical sessions, four-level progressive hands-on cases are constructed, supported by a closed-loop teaching framework consisting of lecture illustration, on-site practice, immediate question-and-answer sessions and class review. After implementing the teaching reform among students, their abilities in mechanical theory application, simulation operation and engineering analysis have been significantly improved. This reform consolidates the foundation for subsequent major courses and offers references for the teaching of similar engineering courses.

1. Introduction

Driven by the concept of Emerging Engineering Education [1], robotics technology is advancing rapidly toward high precision, high stability and strong adaptability, with its application scenarios fully covering core industrial fields such as intelligent manufacturing, automated production lines and precision assembly [2]. In high-end equipment application scenarios, the static performance of robots directly determines operational accuracy and overall machine reliability. Terminal deformation caused by insufficient stiffness of robot links and positioning errors resulting from stress deformation of key components are core factors restricting robot operation quality [3]. In the teaching process of the Robotics Engineering program, after students have acquired foundational mechanics knowledge through courses such as Theoretical Mechanics and Mechanics of Materials, they begin to engage with core specialized courses including Robot Design and Robot Dynamics.

As a pivotal hub connecting fundamental theories with professional practice, Robot Statics Calculation and Simulation focuses on cultivating students' capabilities in mechanical modeling and hands-on finite-element simulation, laying a solid foundation for their further academic study and career development [4].

However, the existing curriculum teaching system fails to fully meet the talent training requirements of Emerging Engineering Education and the cognitive rules of lower-grade students, with obvious deficiencies in statics analysis and simulation teaching. Traditional teaching separates the instruction of elasticity theory and finite element software operation. Abstract mechanical theories cannot be well integrated with practical applications, leaving students unable to establish internal connections between theoretical knowledge and simulation operations. Against the backdrop of Emerging Engineering Education, restructuring the curriculum system and reforming teaching modes to deeply integrate statics and elasticity theories with finite element simulation helps remedy the disconnection between theory and practice in conventional teaching. This approach conforms to students' cognitive development rules and greatly improves their comprehension, learning interest and engineering capabilities [5]. In addition, practical cases in traditional teaching lack hierarchical progressive design. The passive teaching mode, which mostly relies on teacher demonstration followed by student replication, leads to a common problem: students can complete operations in class but struggle to finish tasks independently after class, making it hard for them to form a complete chain of engineering practical abilities. In summary, severe disconnection between theory and practice prevents students from proficiently applying tools such as finite element methods to solve complex structural and robotics-related problems, directly impairing their learning outcomes and practical engineering competence. Such capacity deficits not only hinder their specialized study, but also further weaken their comprehensive practical engineering capabilities in future careers [6].

To address the above-mentioned teaching difficulties, this paper carries out teaching reform practice for the 64-hour course Robot Statics Calculation and Simulation (32 hours of theoretical teaching and 32 hours of practical training) targeting students majoring in Robotics Engineering. Guided by the philosophy of Emerging Engineering Education [7], the course restructures its teaching system with the deep integration of theory and practice as the core principle, and integrates the teaching of elasticity theories and basic Abaqus operations simultaneously. The practical teaching content is optimized to build a hierarchical simulation hands-on case system ranging from component parts, structural components to complete systems. A closed-loop teaching framework consisting of case explanation, on-site practice, timely question-and-answer communication and class review is adopted. This reform aims to strengthen students' practical capabilities in finite element simulation and their ability to solve engineering problems, cultivate interdisciplinary engineering talents that meet the demands of intelligent manufacturing, and provide referable practical approaches for the teaching reform of similar undergraduate courses on mechanical simulation.

2. Analysis of Current Teaching Status and Core Pain Points of the Course

As a basic disciplinary course for students majoring in Robotics, Robot Statics Calculation and Simulation serves as a critical link connecting fundamental mechanical knowledge and engineering practical applications. Targeting students in the transition phase from basic theories to professional skills, the course needs to balance consolidation of abstract mechanical principles and hands-on operation of simulation software. Nevertheless, combined with the current course implementation and students' learning characteristics, prominent deficiencies remain in four core dimensions: theoretical teaching, practical teaching, integration of theory and practice, and assessment methods, which directly hinder teaching effectiveness and the improvement of students' comprehensive abilities.

(1) Theoretical Teaching

Elasticity theory is inherently abstract, involving concepts such as stress-strain relations, constitutive equations and boundary conditions. Having just finished the courses of Theoretical Mechanics and Mechanics of Materials, students possess limited capabilities in applying advanced mechanical theories. In conventional teaching, elasticity theory and finite element simulation software are taught separately. As a result, students fail to correlate theoretical formulas with software operations. For instance, after learning constitutive equations, they do not know how to define material parameters in the software, which prevents theoretical knowledge from being transformed into practical operational capabilities.

(2) Practical Teaching

The design of traditional practical cases fails to fully consider students' learning rules for software operation, and the difficulty level lacks gradual progression. Meanwhile, the teaching mode remains passive, featuring one-way instruction of operating procedures by teachers and mechanical replication by students. There is a lack of timely responses to students' individual questions during class, and no systematic review and summary after class. Consequently, students can complete operations with teachers' guidance in class, yet they do not know how to tackle new practical cases independently after class, and fail to develop genuine independent problem-solving capabilities.

(3) Connection Between Theory and Practice

There exists a noticeable time-gap between theoretical lectures and practical sessions. Practical application is conducted weeks or even longer after theoretical content is delivered. Limited by students' knowledge retention and heavy academic workload from multiple courses, previously-learned theoretical knowledge is easily forgotten during the interval. Consequently, considerable time in practical classes has to be spent reviewing theories, which takes up hands-on practice time. This makes it difficult to achieve the teaching objective of integrating theory with practice and greatly reduces teaching efficiency.

(4) Assessment Methods

Traditional assessment mainly relies on the final written theoretical examination and practical simulation reports. It only focuses on students' final scores, while failing to evaluate students' in-class application of theories, standardization of practical procedures (such as the rationality of software operation steps and scientific nature of parameter settings), and independent debugging capabilities when encountering simulation errors. Such an assessment scheme cannot objectively reflect students' actual abilities and hardly stimulates students' enthusiasm for in-class practice.

These four major pain points are intertwined. They not only restrict the efficient utilization of teaching resources, but also fail to meet students' demands for consolidating theoretical knowledge and improving practical skills, making it difficult for the course to achieve the established teaching objectives. Accordingly, targeted and systematic optimization to address these problems is the key to improving teaching quality and fostering students' core professional competencies.

3. Overall Design of Curriculum Teaching Reform

3.1. Core Concept

This teaching reform is carried out with four objectives: adapting to students' learning status, integrating theory with practice, conforming to the progressive law of students' ability development, and realizing closed-loop teaching of the course. Considering that students have a weak foundation in mechanics and no prior experience in software operation, elasticity theory and basic Abaqus applications are taught in an integrated manner. Practical cases are designed following the principle from simple to complex and from individual parts to complete systems. Adopting the teaching route of theoretical explanation, immediate connection of knowledge, hands-on case practice and review consolidation, closed-loop cultivation of knowledge and capabilities is realized. Ultimately, students are enabled to master the fundamental skills covering elasticity modeling, Abaqus simulation and case analysis.

3.2. Theoretical Sessions (32 Hours): Integrated Teaching of Elasticity Theory and Fundamental Abaqus Operations

The fundamental knowledge points of Abaqus are decomposed and matched one-to-one with the core contents of elasticity theory to realize synchronous instruction and immediate knowledge connection. This design enables students to observe corresponding operations in the software while learning theoretical knowledge, so that they can understand how to apply theories immediately after learning them. Meanwhile, the allocation of the 32-hour class hours fully considers students' learning conditions. By emphasizing key points and simplifying difficult concepts, the course content is made more accessible.

The 32 theoretical hours are divided by knowledge modules, and each module adopts the integrated teaching mode combining elasticity theory and basic Abaqus applications. The curriculum consists of five modules:

Module 1 (6 hours) covers fundamental assumptions of elasticity, stress-strain relations and Hooke's law, corresponding to Abaqus operations including software interface familiarization, geometric modeling of parts and material property definition;

Module 2 (8 hours) illustrates equilibrium equations, geometric equations and boundary conditions, together with load application, boundary condition assignment and basic meshing in Abaqus;

Module 3 (8 hours) introduces solution strategies for elastic problems and static analysis of simple components, combined with basic Abaqus operations such as step definition, job submission and post-processing (e.g., viewing stress and strain contours);

Module 4 (6 hours) presents the basic principles of finite element analysis, sorts out the overall finite element simulation workflow in Abaqus, and guides students to complete full simulation procedures for simple parts;

Module 5 (4 hours) focuses on elastic modeling of typical robot structures (such as links and joints), supported by comprehensive instruction on modeling and simulation of basic robot components in Abaqus.

3.3. Practical Sessions (32 Hours): Design of Hierarchical Hands-on Case System

Robot statics analysis cases are designed in four progressive levels: part level, component level, system level and comprehensive optimization. The difficulty of cases increases gradually, conforming to students' learning rules for mastering software operations. The practical teaching is divided into four sessions, with 8 hours for each session. Every session consists of case explanation (2 hours), on-site student practice (4 hours), timely question-and-answer communication (1 hour) and class review (1 hour), aiming to address the common problem that students can complete operations under teachers' guidance but fail to work independently. The detailed arrangement of the four practical sessions is as follows.

The first session centers on static simulation of industrial robot links, focusing on geometric modeling of single parts, material assignment, application of loads and boundary conditions, and post-processing operations.

The second session carries out static simulation for assembled structures composed of robot joints and links, with emphasis on assembly modeling, contact definition and multi-load-case analysis. Teaching focuses on assembly and contact issues, while practice highlights the capability of multi-condition simulation, enabling students to handle simulation tasks of assembled components.

The third session takes the body of a desktop collaborative robot as the simulation object and emphasizes simplification techniques for system-level modeling. The content is tailored to the academic level of students without excessive complexity. Students are required to independently design simulation schemes and conduct overall modeling, systematic load analysis and stiffness performance evaluation, so as to develop preliminary capabilities in simulation scheme design.

Based on the hands-on achievements from the previous three sessions, the fourth practical session focuses on static deformation optimization simulation of robot links. Teachers first introduce optimization ideas, followed by group-based student practice. Students adjust structural parameters such as wall thickness and cross-sectional shape according to stress and strain contours and complete optimization verification. Group consultation, achievement exchange and comprehensive review are arranged in the end. The objective is to equip students with the ability to analyze structural static performance based on simulation results and possess preliminary simulation optimization capabilities.

3.4. Teaching Methods

Considering the learning characteristics of students, three operable teaching methods are adopted to improve classroom efficiency.

(1) Focused Instruction and Ample Practice

In theoretical sessions, the derivation of abstract formulas is reduced, with emphasis laid on the engineering significance of formulas and software application approaches. Practical sessions prioritize student practice supplemented by teacher instruction, ensuring students have sufficient time for hands-on operations.

(2) Team Collaboration

In practical sessions, students are divided into heterogeneous groups of 2–3 members, mixing students with solid foundations and those with weaker foundations. Group members discuss problems with one another during practice, and teachers provide targeted tutoring for less proficient students. This approach alleviates the insufficient time available for one-on-one guidance to a certain extent.

(3) Immediate Feedback

Teachers offer timely feedback on small exercises in theoretical classes and the hands-on process in practical classes, enabling students to identify and resolve problems on the spot and preventing the accumulation of misconceptions.

4. Teaching Implementation Effect

This course has been implemented for the Robotics Engineering major at the University of Shanghai for Science and Technology. The class consists of 43 students over a period of 16 weeks. After systematic integrated teaching and hierarchical hands-on training, students have achieved remarkable improvements in core capabilities including theoretical modeling, software operation and comprehensive engineering analysis. The specific outcomes are presented as follows.

(1) Theoretical Comprehension and Modeling Ability

The synchronous integrated instruction of elasticity theory and Abaqus operations effectively lowers the cognitive barrier for students to understand abstract mechanical concepts. Final examination data indicate that more than 85% of students are capable of independently establishing force models of robots and making reasonable mechanical judgments. Compared with previous cohorts who did not take this reformed course, the improvement is remarkable, which verifies that students' theoretical comprehension and independent modeling ability have been greatly enhanced.

(2) Simulation Operation and Engineering Application Capabilities

Through hierarchical case training in practical sessions, students' hands-on capabilities in Abaqus have achieved a leap from zero foundation to independent application.

Part-level simulation: All students in the class can independently complete 3D geometric modeling, material property definition, meshing, application of loads and boundary conditions, as well as post-processing contour visualization with complete and standardized operation procedures.

Component-level and system-level simulation: The vast majority of students are able to handle component-level simulation tasks involving assembly contacts and multiple load cases. Approximately 70% of students can independently complete simplified modeling, static simulation and stiffness evaluation of the complete robot system, acquiring preliminary capabilities to tackle complex simulation tasks.

(3) Comprehensive Problem-Solving Capabilities

In the final comprehensive project, students were required to work in groups to complete the whole workflow for robot statics analysis, including problem definition, simulation scheme design, computational analysis and proposal of optimization suggestions. The project outcomes demonstrate the following results:

Comprehensive analysis capability: Students can systematically analyze link deformation and stress distribution, and put forward reasonable optimization schemes such as adjusting wall thickness and arranging stiffeners based on simulation results. They have fully mastered the application workflow of finite element analysis in engineering problems.

Teamwork and communication skills: Clear task division was implemented within each group. Students achieved remarkable improvements in collaboration and communication throughout the project, and further consolidated relevant knowledge and skills via teamwork.

5. Conclusions

In the context of Emerging Engineering Education, this paper addresses core pain points existing in the teaching of Robot Statics Calculation and Simulation, including the abstract nature of elasticity theory, disconnection between theoretical knowledge and hands-on practice, lack of progressive practical cases, and monotonous assessment methods. Taking the deep integration of theory and practice as the main line, this study carries out exploration and practice of teaching reform for the 64-hour course (32 hours for theoretical teaching and 32 hours for practical training).

In theoretical teaching, an integrated teaching system combining elasticity theory and basic Abaqus operations is reconstructed to realize synchronous instruction and immediate knowledge connection, which lowers students' cognitive barriers. In practical teaching, a hierarchical case system ranging from part level and system level to comprehensive optimization is established. Combined with the closed-loop teaching mode consisting of case explanation, on-site practice, timely Q&A and class review, the reform effectively solves the problem that students can follow operations in class but struggle to work independently after class. Meanwhile, three supporting teaching methods — focused instruction and ample practice, team collaboration and immediate feedback — are adopted to improve classroom efficiency.

Teaching practice verifies remarkable reform outcomes. More than 85% of students are able to independently complete static modeling of complex structures, and most students have mastered simulation analysis capabilities covering part level to system level. The final comprehensive project effectively cultivates students' ability to tackle practical engineering problems using theoretical knowledge and simulation tools, as well as their teamwork literacy.

Future research will further advance in developing special simulation cases for typical robot application scenarios, exploring artificial intelligence-assisted learning tools, and constructing a diversified formative assessment system. It is expected to provide referable reform approaches for the teaching of similar mechanical simulation courses for lower-grade students.

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