Bridging Theory and Application: A Project in System Dynamics Course

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Abstract

System dynamics can be abstract and mathematically complex to students as it requires knowledge of mathematical modeling and analysis of systems. Practical projects and labs can help students reinforce the concepts and observe the real-world applications. Most importantly, they can be used to foster students' interest in the subject. This work-in-progress paper describes the implementation of a project incorporated system modeling and verification into a junior-level system dynamics course in the mechanical engineering curriculum. The project required students to mathematically model a practical mechanical system and determine the values of the system parameters based on the experimental data. They verified the values of the parameters by comparing the numerical and experimental responses. Students reinforced their learning and connected the real-world application to the theory throughout the process. The project was first introduced in the fall 2023 semester. An anonymous survey was conducted at the end of the project regarding the learning outcomes for the course. Based on the results of the survey and students' performance on the questions, the project strengthens students' abilities in system modeling and analysis.

Keywords

Engineering education, System modeling and analysis

Background and Introduction

System dynamics typically provides students with an introduction to the fundamental concepts, tools, and methodologies used in system modeling and analysis. This course introduces topics including system modeling using differential equations, transfer function, block diagram, state space approach and system response analysis in the time and frequency domain. The students find the course content theoretical and abstract. To help students connect the theory to the real-world application, a typical undergraduate system dynamics course will employ some combination of lab experiments, and projects. Practical course projects can motivate students' interests in the subject and help reinforce the knowledge learned in class. Due to the high cost of lab equipment, instructors have developed projects utilizing simulation software such as Simulink, MATLAB, Python etc. [1,2]. There are also instances where multiple lab groups must share one lab equipment to save the cost of lab equipment. However, for a large class size, the waiting time on the lab equipment can be protracted. Instructors have also developed lab activities based on portable and low-cost microcontrollers and sensors which make the lab equipment more accessible for students [3,4].

The system dynamics course is a required, three-credit hour course for mechanical engineering majored students at Utah Valley University. Typically, students usually take this course during their junior year. It comprises solely lecture-based instruction without any lab components. Introducing a practical project can serve as a valuable means to connect theoretical concepts with real-world applications. The learning outcomes of the course are as follows:

- Develop the governing equation for a mechanical system.
- Represent the transfer function for a system.
- Describe the analogy between mechanical and electrical systems.
- Represent a system in state space.
- Predict a system's response by solving its governing differential equation.
- Describe the effect of mass, stiffness, and damping on a mechanical system response.
- Predict the behavior of a vibratory system.
- Perform simulation of the behavior of a system with computer software.

To enhance students' achievement of the course learning outcomes, a course project was incorporated into the class. This project consists of two parts, part 1: system identification and part 2: system verification. Through the projects, students consolidated their knowledge of mathematical modeling of mechanical systems using different approaches.

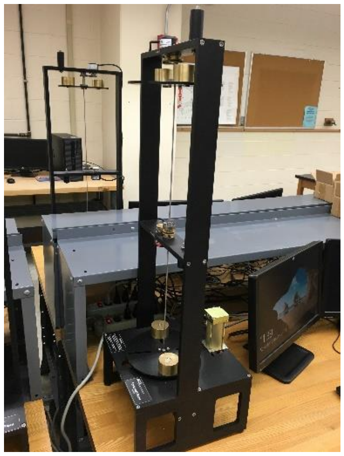


Fig. 1 ECP Torsional Plant

Rotational Mechanical System Modeling Project

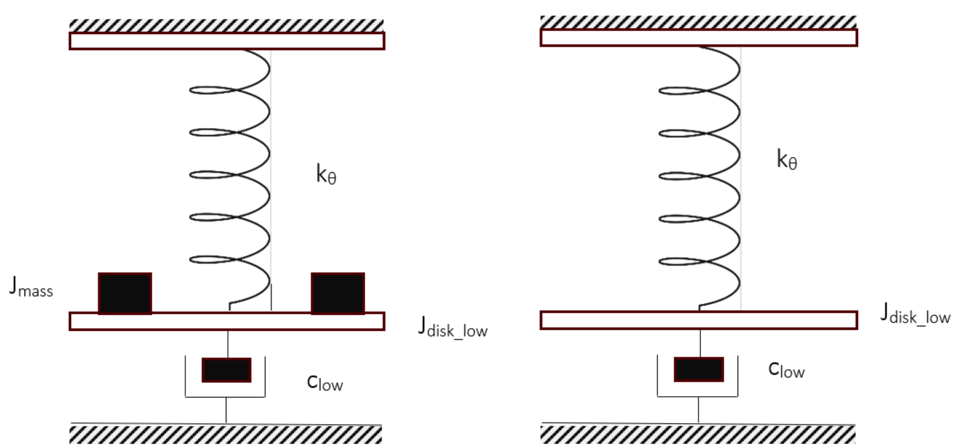
ECP Torsional System as shown in Fig.1 is an educational platform that is mainly used for undergraduate vibrations and controls courses. It includes three disks with adjustable inertias, and a torsional spring which together can be modeled as single and multiple degrees of freedom mass spring damper systems. The project for this class utilizes experimental data from this equipment.

The project was designed to encompass two different parts. The first part of the project was to determine the physical parameters of a two-degree of freedom torsional system. The system is set up as a single-degree-of-freedom (sdof) classical spring mass damper system by securing either the upper or lower disk. Fig.2 displays diagrams of four distinct configurations, while the corresponding experimental angular displacements of the disks are illustrated in Fig.3. Based on the free responses of disks, the inertia of the disk, J_{disk} torsional spring stiffness, k_θ and damping coefficients, c of the torsional system were calculated. Additionally, students drew the free body diagram and derived the equation of motion of the torsional system. Throughout the process, students had a better understanding of the modeling process of a practical mechanical system.

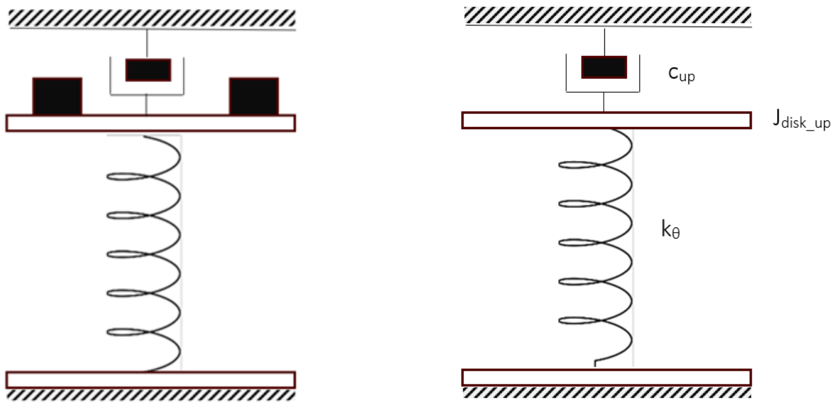
In the second phase of the project, students verified the values of the system parameters and the mathematical model. They proceeded to derive the state space representation of the torsional system, followed by simulation of the proportional and derivative (PD) control response using Simulink. Given that control system design falls outside the class's scope, a pre-prepared Simulink program for PD control with predetermined proportional and derivative gains was provided to the students. Primarily, students were tasked with revising the state space block by inputting the matrices of the state space model. The Simulink program and simulation responses are depicted in Fig.4. The experimental PD response was provided to the students. They compared the results between the simulation and actual test then commented on how well the numerical results matched the experimental results. Fig. 5 shows the comparisons between the experimental and numerical responses. Students had to revise their model or parameters calculations if their results didn't match well.

Since students don't have access to the lab equipment, a few videos explaining experimental setup and lab procedures were posted on Canvas. For each part of the project, the instructor provided students with a lab manual and experimental data. Students worked in groups on both parts of the project. Each team submitted a team contract at the beginning of the project. At the end of each part of the project, every group had to submit a report. A report template and evaluation rubric were also provided to the students. Throughout the project, the following course learning outcomes were assessed.

- Develop the governing equation for a mechanical system.
- Derive the state space representation of a mechanical system.
- Predict the response of a system using software.
- Describe the effect of inertia, stiffness, damping elements on a mechanical system response.

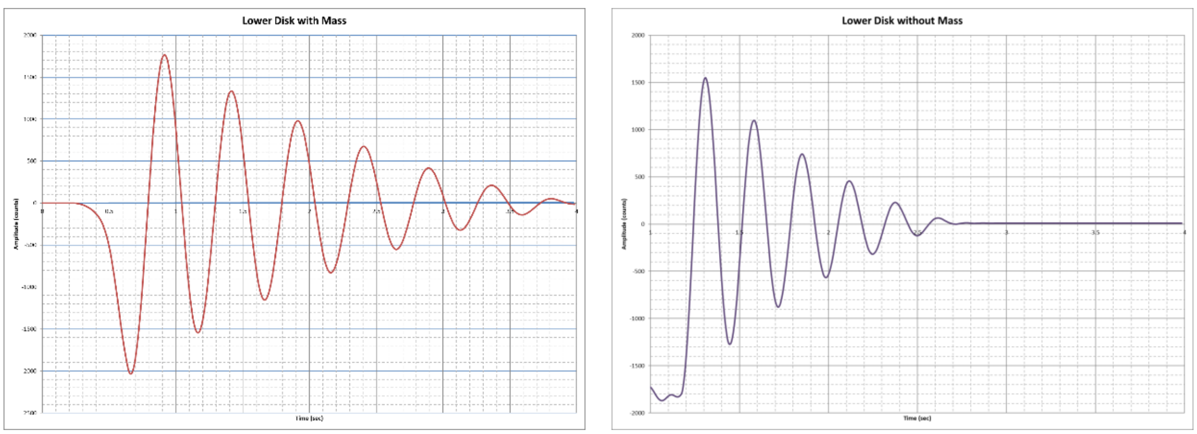


(a) (b)



(c) (d)

Fig. 2 Diagrams of sdof torsional systems with (a) top disk clamped and masses attached to the bottom disk (b) top disk clamped and no mass on the bottom disk (c) bottom disk clamped and masses attached to the top disk (d) bottom disk clamped and no mass on the top disk



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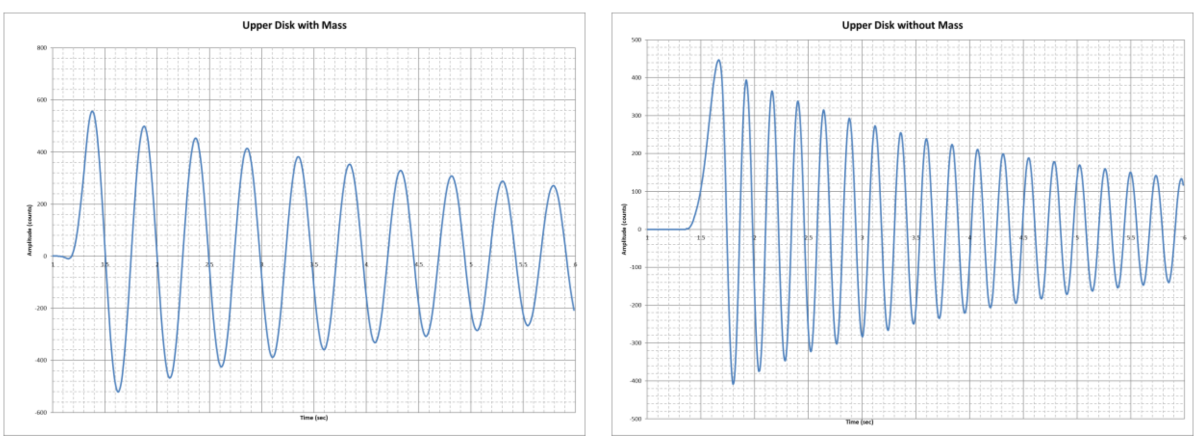


(c) (d)

Fig. 3 Free responses of the disks (a) angular displacement of the bottom disk with masses (b) angular displacement of the bottom disk without mass (c) angular displacement of the top disk with masses (d) angular displacement of the top disk without mass

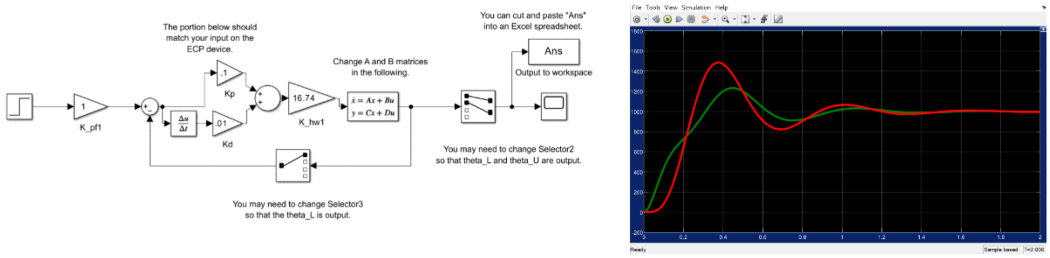
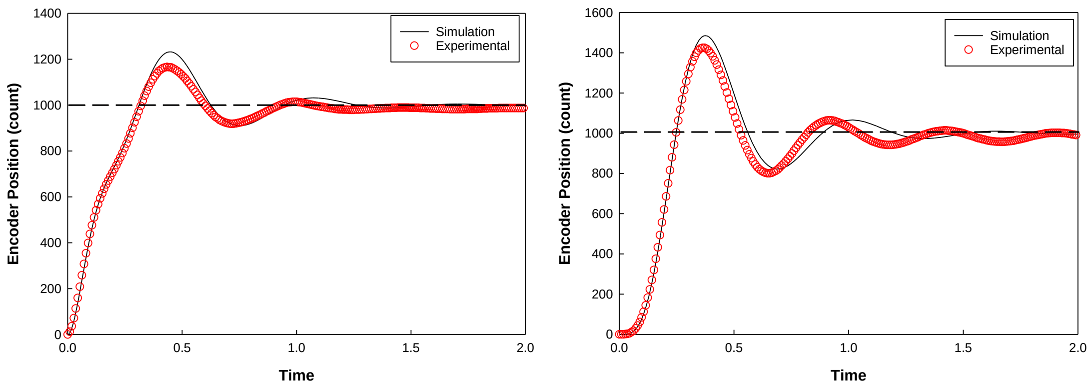


Fig.4 Simulink program and numerical responses



(a) (b)

Fig. 5 Comparisons between experimental and simulation responses (a) top disk (b) bottom disk

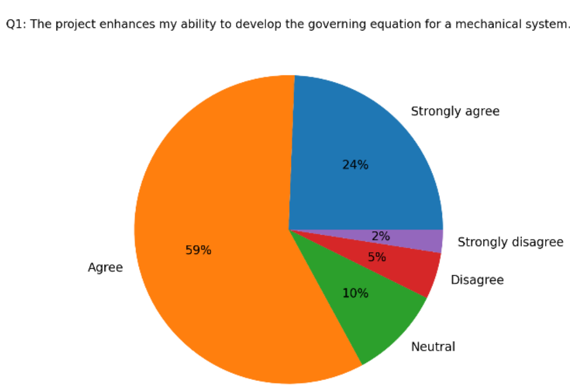
Project Experience Survey

The system dynamics course was taught using the face-to-face mode in the Fall 2023 and Spring 2024 semesters. At the end of the Fall 2023 semester, a survey was created and conducted to learn about students' experience with the project. A total of 42 students enrolled in two sections of class have completed the survey. The questions in the survey are listed in Table I. Responses to the survey questions Q1 to Q8 were on a 5-point Likert scale. (5 – strongly agree/excellent/very challenging, 4 – agree/good/challenging, 3 – neutral/fair/moderate, 2 – disagree/poor/easy, and 1 – strongly disagree/very poor/very easy). Fig.6 (a) to (f) present the results of Q1 to Q6 respectively. As can be seen from Fig. 6 (a), about 83% of students Strongly Agree and Agree that the project enhances their skills to develop governing equation of a mechanical system. The response of Q2, shown in Fig. 6 (b), illustrated that 80% of students surveyed either strongly agreed or agreed that the project made them learn how to experimentally determine the system parameters of a mechanical system. The responses of Q3 show that 34% and 44% strongly agree and agree that the project enhances their skills to employ state space approach to model a mechanical system. Q4, shown in Fig. 6 (d), demonstrated that 75% of students strongly agreed or agreed that the project improves my understanding of mathematical modeling of a mechanical system. The responses of Q5, shown in Fig.6 (e), show that 17% and 59% of survey students strongly agree and agree that the project offers me the opportunity to utilize Simulink software to simulate the response of a mechanical system. As presented in Fig. 6

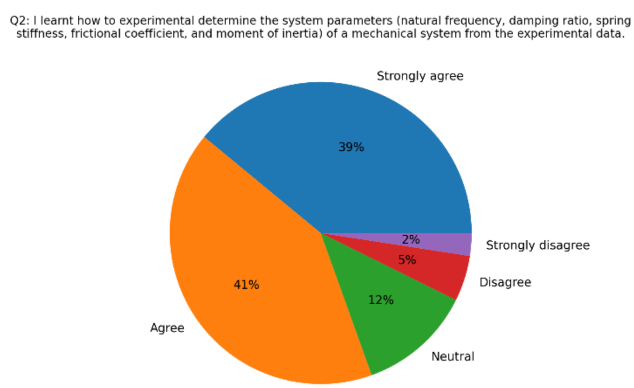
(f), the responses to Q6 corresponding to the strongly agree and agree are 39% and 32% respectively. Q7 is about understanding team collaborations. As shown in Fig.6 (g), 78% of students responded that the collaborations are excellent and good. Based on the results of Q8, 24% and 59% of the students find the project very challenging and challenging respectively. Overall, the results verified that the course project was challenging for junior-level students, however, it helped the students attain the learning outcomes of the course and enhanced their learning of the theoretical knowledge.

Table I: Post-Lab Survey Questions

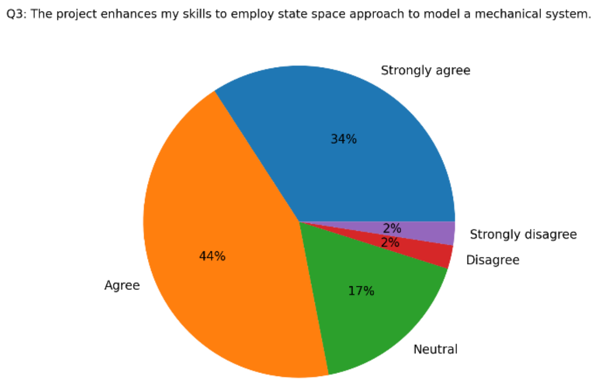
Q1: The project enhances my ability to develop the governing equation for a mechanical system.
Q2: I learnt how to experimentally determine the system parameters (natural frequency, damping ratio, spring stiffness, frictional coefficient, and moment of inertia) of a mechanical system from the experimental data.
Q3: The project enhances my skills to employ state space approach to model a mechanical system.
Q4: The project improves my understanding of mathematical modeling of a mechanical system.
Q5: The project offers me the opportunity to utilize Simulink software to simulate the response of a mechanical system.
Q6: The recorded videos and lab manual are helpful for me to understand the actual experimental setup of the rotational mechanical system without the opportunity to observe the system in person.
Q7: How effective was the collaboration with your project team?
Q8: How would you rate the complexity of the projects?



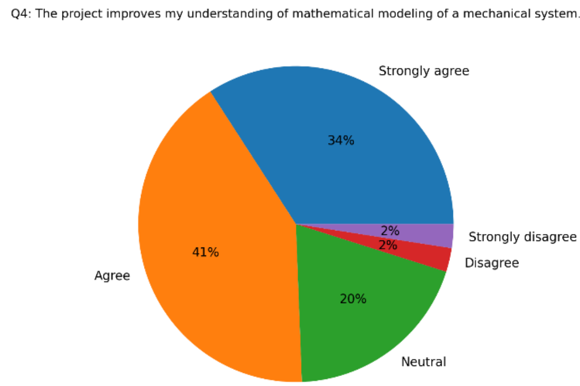
(a) Q1 responses distribution



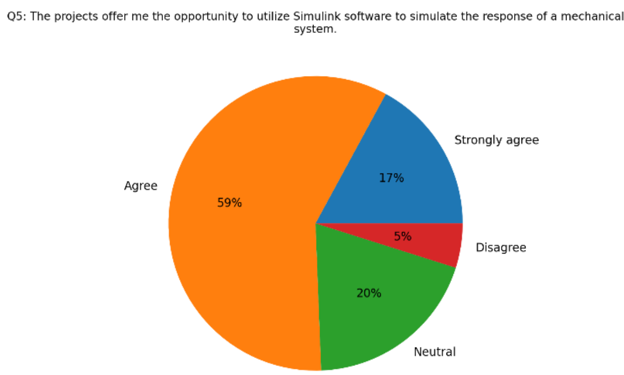
(b) Q2 responses distribution



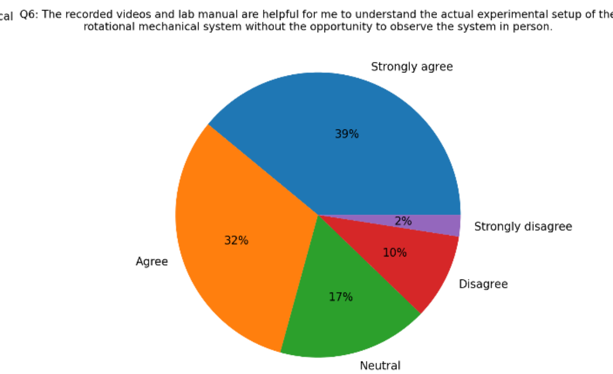
(c) Q3 responses distribution



(d) Q4 responses distribution

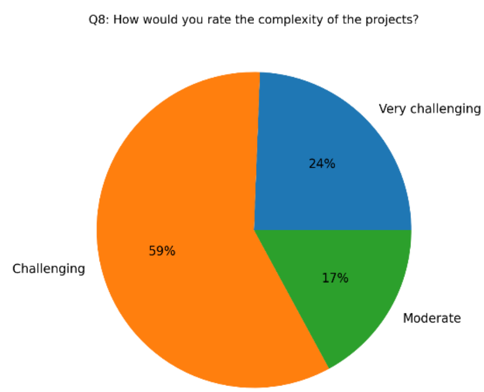


(e) Q5 responses distribution



(f) Q6 responses distribution

(g) Q7 responses distribution



(h) Q8 responses distribution

Fig. 6 Post-Project Survey Results: a) - h) Q1-Q8 responses distributions

Assessment

In addition to the course survey, students' achievement of the course learning outcomes is evaluated through two lab reports, which include their responses to the questions in projects' deliverables. Some of the questions and the corresponding students' performance are presented below:

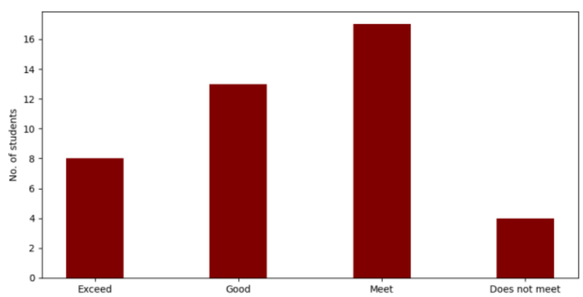
Question 1: Draw the free body diagrams of the torsional systems of four distinct configurations in Fig. 2 and derive the equation of motions.

Question 2: Draw the free body diagram and derive the equation of motion of the two-degree-of-freedom torsional system.

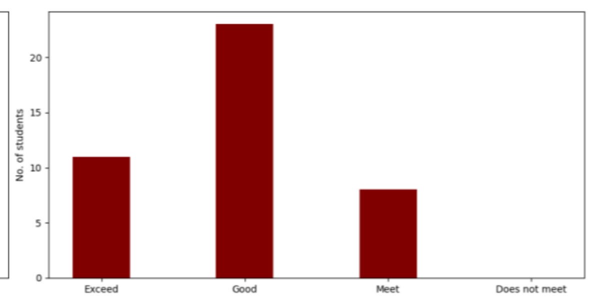
Question 3: Derive the state space representation of the two-degree-of-freedom torsional system.

Question 4: Simulate the PD response of the two-degree-of-freedom torsional system using Simulink.

The students’ responses to Q1 through Q4 are evaluated on a scale from highest designation labeled as “Exceed” to the lowest labeled as “Does not meet”. Figures 7 (a) to 7 (d) present the assessment outcomes of Q1 to Q4 respectively. Students found it more difficult to model rotational mechanical systems than their linear counterparts. It is discernible from the figures that students performed better in Q3 and Q4, regarding state space representation and simulation using software, than Q1 and Q2, related to free body diagram and the equation of motion, respectively.



(a)



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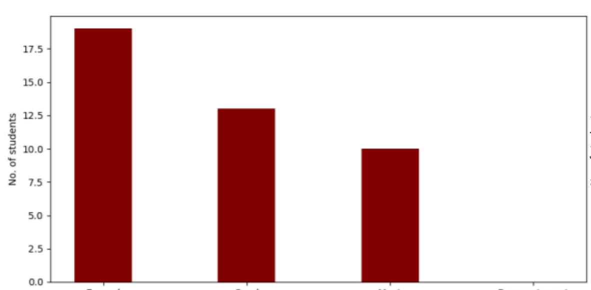

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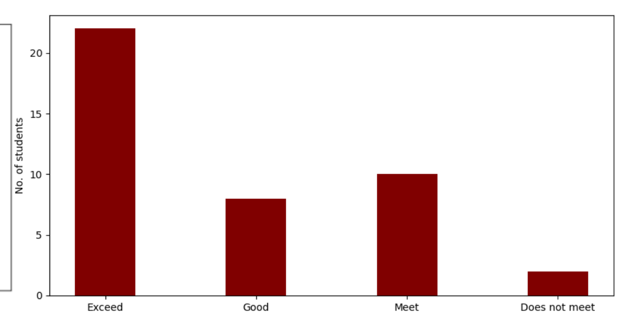

(d)

Fig. 7 Assessment outcomes for (a) Q1 (b) Q2 (c) Q4 (d) Q4

Conclusions

This work-in-progress paper outlines the integration of project-based system modeling and verification into a junior-level system dynamics course within the mechanical engineering curriculum. The project tasked students with mathematically modeling a practical mechanical system and determining system parameters' values using experimental data. Subsequently, they validated these parameters by comparing numerical and experimental responses, fostering a practical application of theoretical concepts throughout the learning process. Initiated in the fall 2023 semester, the project was accompanied by an anonymous survey at its conclusion to gauge its impact on the course's learning outcomes. Survey results indicate that the project effectively enhances students' proficiency in system modeling and analysis.

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