Instrument for Assessing Skills related to Free Body Diagrams in a Sophomore Engineering Mechanics Course

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Abstract

Commonly, engineering faculty members who teach a sophomore engineering mechanics course find that the ability of students to idealize a mechanical system and draw its free body diagram (FBD) is a threshold concept that once mastered can change the way a student progresses through the discipline. While there are inventories available related to engineering mechanics, there is not one solely focused on the intricacies of FBDs of mechanical systems and the inclusion of all independent constraint forces and moments, a crucial skill in engineering. The goal of this study is to develop and validate an instrument for FBDs containing both free response and multiple-choice questions. The objectives in this study include the ability of a student to: properly identify and isolate the system; account for correct constraint forces and moments; utilize Newton's third law; indicate external and internal forces; apply friction when appropriate; identify bodies in motion properly; designate cables, normal forces, and two force members correctly; and specify the effect of gravity correctly.

The instrument developed as part of this study was administered to a set of students taking a typical sophomore mechanics course at a large public institution during fall 2016, along with a smaller group of students used in a pilot study during spring 2016. The paper will describe: 1) details on the alpha and beta versions of the FBD instrument developed; 2) early lessons learned; and 3) results from approximately 250 engineering students who took the beta version of the instrument. After administering the instrument and analyzing the results, faculty members have a better idea of the skill set of students in the course and can adjust course instruction appropriately. Furthermore, there will be evidence to examine the extent to which students are prepared related to free body diagrams at the end of a core engineering science course.

Introduction

Engineering faculty members have long assumed that student knowledge and skill with respect to physics is a major part of the foundation for their progress in studying many engineering disciplines, including mechanical engineering. The importance of physics for success in studying mechanical (and related) engineering disciplines is unquestioned. However, a deeper understanding of the ability of students to isolate and idealize a mechanical system of interest and then draw its Free Body Diagram (FBD) while accounting for independent constraint forces and moments is vital information needed in engineering mechanics instruction. In addition, comparison of the abilities of students to transform knowledge using idealized example problems to real world problems, a key skill in engineering, is also needed. Information in these areas motivate this paper, which intends to address two questions:

1) What do engineering faculty members expect students to know and be able to exhibit related to free body diagrams during a sophomore mechanics course; and
2) To what extent do students satisfy these expectations.

Background

Researchers began to discover that learners offered explanations for physical phenomena at odds with common scientific understanding as far back as the 1960s[1,2,3]. For example, researchers found that many learners believed forces needed to be exerted on bodies so the bodies would continue to move at constant, non-zero velocities. Perhaps the most intriguing result of this research was that learners retained their belief in the alternative explanations, even after instruction. What follows in this section is a brief introduction to works related specifically to statics, including FBDs.

Force Concept Inventory

A pivotal event in the field of conceptual understanding occurred when Halloun and Hestenes synthesized research on understanding (and misunderstanding) of concepts of force and motion to create the Force Concept Inventory (FCI)[4]. Consisting of 29 multiple-choice questions, the FCI assessed a student's understanding of Newtonian concept of force and required a student to select between Newtonian concepts and common sense alternatives

Conceptual Understanding of Statics

In statics, objects do not move. Therefore, many of the questions in the FCI, while relevant to statics, do not directly assess student knowledge of statics. Therefore, researchers have worked to explore how learners understand statics. In approximately 2003, the Statics Skills Inventory (SSI) was released with 12 questions relating to skills learned in statics[5]. It assessed student skills critical to the mastery of statics, and not simply conceptual knowledge, and focused on four groups of skills: vector manipulation, modeling and free body diagrams, equilibrium equations, and manipulation of forces and force systems. As of 2005, the authors were working on developing questions highlighting one skill as opposed to typical engineering problems requiring multiple skills to solve[5].

In 2002, the Statics Concept Inventory (SCI) was developed to detect errors associated with incorrect concepts in statics[6]. The authors of this inventory evaluated the conceptual knowledge and not skill-level knowledge. Authors of the inventory stated that mathematical skills were needed for statics, but they were not a part of conceptual content covered in the SCI. Through the current version contains 27 multiple-choice questions, the SCI focused on five groups of conceptual errors: free body diagrams, static equivalence between different combinations of forces and torques, type and direction of loads at connections, limit on friction forces, and equilibrium conditions. Overall, the largest errors received by students on the SCI have been related to questions on constraints and constraint forces[7].

Mechanics Baseline Test

In addition to assessing how well students understand concepts in physics mechanics, which include statics, physics and engineering faculty members are also interested in abilities of students to solve physics problems. To assess these abilities Hestenes and Wells developed the Mechanics Baseline Test (MBT) [8]. Questions on the MBT focused on learner abilities to solve physics problems in three areas of physics mechanics: kinematics, general principles, and specific forces. Unlike the FCI, the MBT had 26 multiple-choice questions that required students to perform computations to find answers to the questions.

Work on conceptual understanding, including the FCI, SSI, and SCI, has provided considerable information about how students understand (or misunderstand) concepts in many different subjects[4,6,7,8,9,10,11,12,13]. In addition, the MBT provides information about abilities to solve problems in physics mechanics[13].

However, the current concept inventories require students to evaluate FBD concepts from more of a physics perspective rather than an engineering perspective. For example, a physics-based approach might assess a student's ability to account for appropriate forces and moments for a particular contact between two bodies with the idealization of the connection presumed to be known. In this respect, the ambiguity involved in the idealization is not considered and tested. Isolation and idealization is a crucial step in transforming the knowledge one learns using idealized example problems to real world problems. This gap motivates the research described in the following sections to design an instrument that requires this engineering judgment.

Methods

To evaluate the ability of students to idealize a mechanical system and draw its FBD, the authors identified a core, required, sophomore-level engineering science course in the mechanical engineering curriculum at Texas A&M University. While students complete several engineering courses in their sophomore-year, including statics and dynamics, materials, thermodynamics, and numerical methods, the course selected is a statics and dynamics course that resembles many courses in mechanical engineering curricula across the world because it is the most physics intensive and includes direct instruction in FBDs. The curriculum for this course and each of the sections is common among the different sections of the course, and standardized sets of exams are utilized. For these reasons, it is relatively easy to extract necessary data for comparison.

A ten-question, alpha version of an instrument to assess abilities of students with respect to FBDs was created and administered to a group of 29 sophomore-level engineering majors in a statics and dynamics course in the spring of 2016[14]. Students were required to draw FBD diagrams for applications without any aids to help guide them, such as multiple-choice options. Scoring for the questions in the instrument was based on a four-point grading scale with each question being graded in two ways: 1) student's ability to isolate the body of interest and 2) student's ability to account for correct contact or constraint forces.

In fall of 2017, a beta version of the instrument was given to all sections of the mechanical engineering statics and dynamics course, resulting in 339 students completing the instrument. All students enrolled in this course were in the mechanical engineering department. In addition, the instrument was administered to students in an aerospace engineering statics course, which was equivalent to the first half of the mechanical engineering statics and dynamics course. This aerospace engineering course was taken exclusively by aerospace engineering majors. Including the aerospace students, the total number of students completing the FBD instrument was 419 students. A portion of the questions were revised from the alpha version, which included ten work-out questions. The decision was made to pilot multiple-choice questions for five of the ten questions in the beta version to explore more efficiency and timeliness of grading due to the larger number of students participating. Questions 1-5 were multiple-choice questions in this version, and questions 6-10 required students to provide work-out solutions.

Results and Discussion

This section describes details from two administrations of an FBD instrument. In addition, initial results from the beta (second) version of the instrument are included.

Alpha Instrument

Detailed results from the ten-question alpha version of the instrument given to 29 mechanical engineering students in spring of 2016 are discussed another paper related to the study[14]. In the alpha version, a four point rating system was utilized to provide consistency in evaluating results. In addition to common FBD errors noted in previous work by Steif in 2004, such as failure to recognize that the body of interest is isolated at specific contacts, results from the alpha version resulted in the additional errors noted by the authors[15]:

- Failure to recognize the difference between a rigid body and a particle
- Tendency to draw forces at centroids
- Failure to recognize that corresponding mechanical effects are idealized and represented as independent forces and moments
- Failure to properly account for the effect of motor and spring in connections
- Failure to idealize and neglect friction between contacts
- Failure to account for independence of the constraint forces
- Double-count effect of contacts, such as a roller confined to a slot
- Assume incorrect direction for friction
- Add fictitious forces for bodies in motion

Details from the administration of the alpha version were used to refine questions used in the beta version of the instrument.

Beta Instrument

While 419 total aerospace and mechanical engineering students completed the beta version of the FBD instrument, results from 249 students from three different faculty-led sections are evaluated at this time and presented here. Results from all students will be evaluated fully before changes to the FBD instrument are implemented for fall of 2017.

Item difficulty index

The item difficulty index measures the difficulty of a single test question. The authors selected to calculate this index to provide a measure of discrimination for the questions, similar to information obtained from an average score. Calculated by taking the ratio of the number of correct responses on each question to the total number of students who attempted the particular question, the index ranges from 0 to 1. A larger value for the index signifies a higher percentage of respondents answered the question correctly, so the item was easier for this population. If the index value is 1, this signifies that all of the participants answered the question correctly. If the index value is 0, no one was able to answer the question correctly. Therefore, a value of 0 or 1 does not discriminate very well. For questions with these index values, it is important to further investigate whether a question was poorly presented or if the students did not have that particular skill at the time of evaluation. While there are a number of different possible criteria for acceptable values of the item difficulty index, a widely adopted criterion requires the value to be between 0.30 and 0.70 within+/-.20 of the optimum value of 0.50[16].

Figure 1 depicts the item difficulty index for the beta physics instrument. Results are shown for the calculated index in terms of number of instrument questions related to each score. The mean difficulty index of the responses in the beta version of the FBD instrument given in fall of 2016 is 0.4. Simply because responses to a question fall outside of the optimum range of 0.30 to 0.70 does not nullify the question, but it does signify the need for closer inspection. The four questions that warrant further review are questions 6, 7, and 8 with an index value of 0.1, 0.2, and 0.1, respectively, and item 1 with an index value of 0.8. As discussed earlier questions 6-8 correspond to three of the five work-out problems in the instrument. Table 1 details the four questions on the opposing ends of the item difficulty index range.

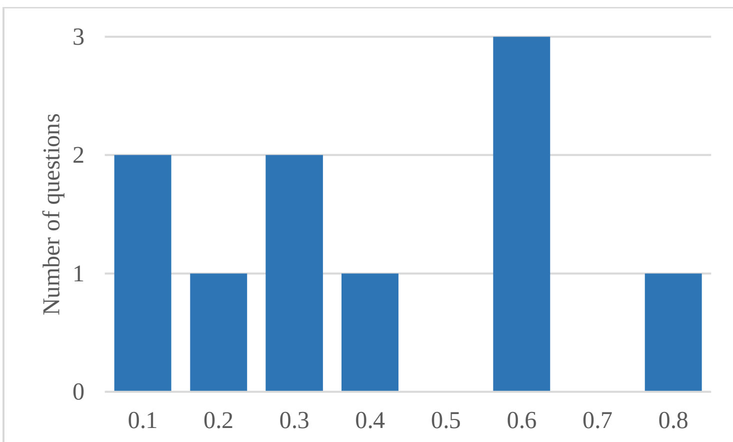
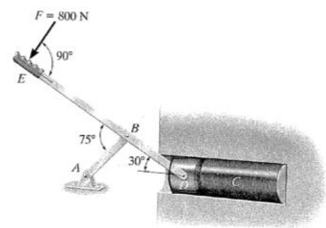
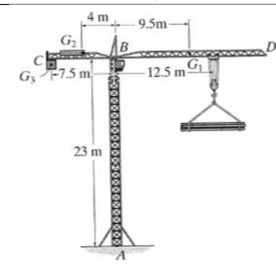
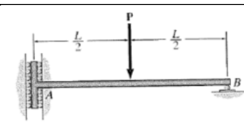
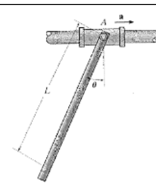


Figure 1. Item difficulty index for the beta physics instrument in terms of number of questions per index score.

Table 1. Questions from beta version of instrument with highest and lowest item difficulty index values.

Question # and type	*Item Difficulty Index Value*	*Question Statement*	*Question Image*
6 work-out	0.1	The piston and link mechanism is used to crush recycled cans. Draw an idealized FBD for the smooth piston.	
8 work-out	0.1	Draw the idealized FBD for the entire tower crane appropriate for equilibrium analysis.	
7 work-out	0.2	Draw the FBD for the T-bar AB.	
1 multiple-choice	0.8	The swinging rod is pin connected to a collar that smoothly slides with an acceleration, **a**. Select the most nearly correct FBD for the rod along with the collar.	

Average scores received

Another similar method of analyzing data is to examine average scores for the questions. A comparison of average scores received for each of the questions in the beta version for the three sections, (with corresponding section numbers of 501, 502, and 503), is shown in Figure 2. Items were scored as either being incorrect (zero points) or correct (one point), which provides a similar scale to the discrimination index. While there are similarities between sections for most of the questions, there is a definite outlier in this analysis related to question 4. In addition, questions 2 and 9 also warrant further review with one section scoring much higher than the other two sections.

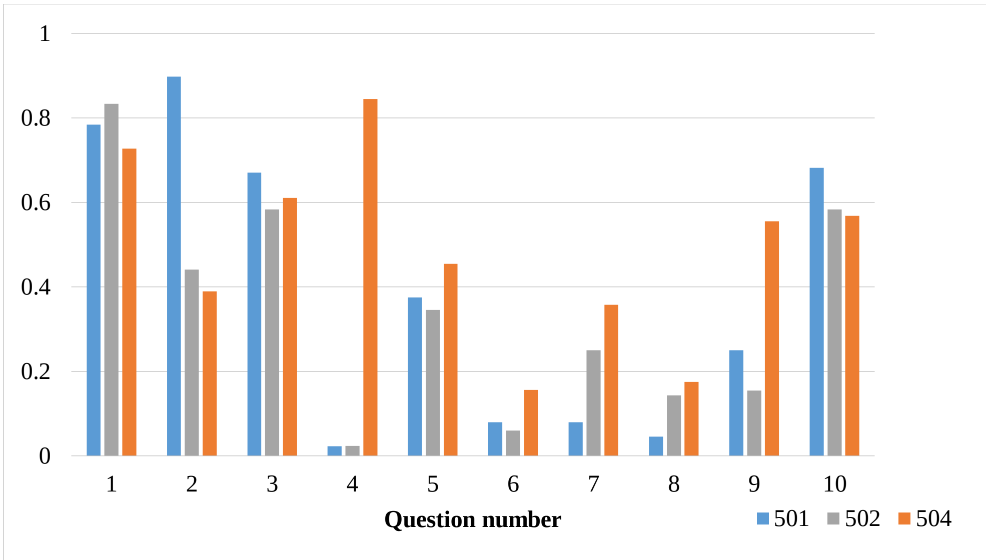


Figure 2. Comparison of average scores received for three sections of students on the beta version of the instrument.

A significant difference between the alpha and beta versions of the FBD instrument is the inclusion of multiple-choice questions. To evaluate how students perform on multiple-choice and work-out type FBD problems, questions relating to similar concepts were asked in both parts. The data was then compared by section to determine how students performed. Results showed that students in all three sections scored almost twice as high on the multiple-choice questions versus the work-out counterpart questions. It is beyond the scope of this paper to address these differences.

Conclusion

After administering two versions of an instrument to assess skill levels of sophomore-level aerospace and mechanical engineering students related to FBDs and analyzing preliminary results, the authors have identified strengths and weaknesses of their students related to FBDs. Using this information, faculty members can better modify instruction in the classroom related to FBDs. While preliminary data indicates several questions need to be investigated further based on item difficulty index scores, further evaluation is needed to distinguish effects of question type, such as multiple-choice versus work-out. An in-depth analysis of data related to all 419 students is on-going by the authors. Information learned through this examination will provide knowledge to further enhance the next version of the FBD instrument to be given in fall of 2017.

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