AC 2007-1331: ENHANCING LEARNING IN MECHANICAL DESIGN USING A MODEL ELICITING ACTIVITY

Brian Self, California Polytechnic State University

James Widmann, California Polytechnic State University

Enhancing Learning in Mechanical Design using a Model Eliciting Activity

Abstract

Traditionally, students in Mechanical Engineering are taught to approach design from a failure perspective. Mathematical models for stress, strain, strength and failure are typically presented in a lecture format and reinforced though the solution of homework problems. The students are then asked to integrate this knowledge during the solution of more or less open-ended projects to gain experience in the design process. This paper reports on a different method of reinforcement of mathematical models and failure concepts through the use of Model-Eliciting Activities (MEA).[1] An MEA is a client driven problem that requires the students to develop a mathematical model not explicitly stated in the assignment. The client driven approach can create an environment where the students value abilities beyond using the traditional prescribed models and algorithms.[2] While traditional design projects focus on the product being developed, MEAs focus on the process of problem solving and model development. The originators of MEAs propose six primary principles to utilize when developing a new problem.

1) The Model-Construction Principle requires that the students come up with a procedure for explaining a "mathematically significant" situation and stresses discovery learning.
2) The Reality Principle puts the problem in context and offers a client who needs a realistic engineering solution to a problem.
3) The Self-Assessment Principle enables students to analyze their problem solutions and revise their approach to open ended problems.
4) The Model Documentation Principle teaches students to create a mental model of their process in solving the problem. Documentation of their model and solution is often in the form of a memo to the client.
5) The Generalizability Principle asks students to develop models that other students (and the client) could easily use, and models that can be adapted to other similar situations.
6) The Effective Prototype Principle ascertains that the problem is relatively simple to implement but still solves the given problem.

Based on these principles, an MEA was created and implemented in a junior level mechanical design course to help students develop a deeper understanding of their newfound knowledge in predicting fatigue failure. Assessment of student outcomes is made through student surveys, a grading rubric, and a Quality Assurance Guide.

Introduction

The ability to assimilate different information and create usable models is a critical skill for engineers. Equally important is the ability to frame and solve ill-defined problems. A fairly new technique which evolved in the mathematics educational community attempts to address these skills by creating problem sets called Model Eliciting Activities (MEAs)[1]. Teams of students are provided with a client-driven problem, most commonly in the form of a request from a fictitious company. These problems are open-ended and force the students to fuse information in a way that is not typically encountered in homework problems. The process of working in a team-based environment, developing a systems-based approach to solving the problem, plus developing and refining conceptual models are all important skills that can be learned in an MEA (in addition to its technical content). Developing higher-order thinking and strong problem solving strategies are as (or more) important to a working engineer as their technical knowledge.

The MEA has several salient differences from other problem-based exercises[4]. Traditional exercises typically involve selecting the correct equations, applying a "cookbook" approach, and coming up with a correct answer. Laboratory exercises and creative hands-on exercises in engineering classrooms often have a similar approach. MEAs require students to develop a model, conceptual and/or mathematical, then refine it by comparing it to the customer needs. This design, test, revise cycle is the crux of many undergraduate design courses. These MEAs can begin the process of developing strong open-ended problem solvers before students are required to complete a year long capstone design project.

Diefes-Dux et al.[2] discuss a useful framework to use when developing an MEA. There are six basic principles that should be used[2,5.]

1. Model Construction: The MEA should require students to develop a process, description, and/or a mathematical model to address the needs of the client. This is not constrained to simply a mathematical equation – it may take the form of a set of procedures, an algorithm, a set of instructions, or graphical models. There should also not be one correct answer – students should struggle with the open-ended nature of the MEA. It is also beneficial if a certain degree of discovery learning takes place in the process.

2. Reality: A true engineering-based, client-driven problem should be motivational and realistic for the student. Placing lecture and textbook knowledge in an industrial or research context will help students realize how their skills may be used in the future.

3. Self Assessment: The MEA should include sufficient criteria for the student to test and possibly change their conceptual/mathematical models. As shown in our Fatigue MEA in the appendix, this often comes in the form of sample data. Team members should be able to assimilate their previous knowledge to make some judgment on the quality of their solutions.

4. Model Documentation: A written, deliverable product should be produced at the end of the MEA. This is typically in the form of a memo to the company, but could also be in the form of a computer program, algorithm, or even a physical product. Their documentation helps students to review and reflect upon the development of their model, and allows the instructor to examine the students' conceptual understanding of the material and their problem solving strategies.

5. Generalizability: The solutions to the model should be readily usable to the client – this requires that the product memo be clear, well-written, and easy to implement. A strong MEA also requires the solution to be readily adaptable to similar problems or situations. In our Fatigue MEA, students were asked to adapt their model to shafts that had been shot-peened. This is

often difficult for the students, who tend to create very specific models for the exact problem they are given.

6. Effective Prototype: Student teams should be able to produce a solution that is "as simple as possible yet still mathematically significant."[2] The teams should be asked to revisit the model repeatedly as they progress, making sure that their models employ sound engineering principles.

Methods

The MEA described in this paper was developed for a junior level course in mechanical design. This is a required class where mechanical engineering students attend lecture three days each week (MWF) for 50 minutes in maximum lecture class sizes of 36. The students also attend a weekly three hour "laboratory" section with a maximum of 24 students. The lecture portion of the course begins with a thorough review of Strength of Materials and adds knowledge of failure theories to allow the students to analyze structural designs. Other lecture topics include design for stiffness, advanced stress analysis, and fatigue failure theories with applications. The laboratory portion of the course consists of various design and analysis exercises that reinforce lecture materials and allow students to apply the theories to solve open-ended design problems. For the fall quarter of 2006 the lab exercises consisted of three open-ended design problems (one involving the construction of a steel structure that was tested to failure), two analysis problems using computation tools (a stepped shaft deflection analysis and a finite element analysis exercise) and during the last week of the class, the Fatigue MEA. For the fall quarter there were 57 students enrolled in the course, which was divided into three lab sections (15, 24 and 18 students for each section).

The Fatigue MEA was developed by modifying an existing fatigue analysis exercise that had been developed and used in previous quarters by several professors spanning several academic years. The main goal of this exercise was to give students the experience with the process of a complete fatigue analysis for a typical torque carrying shaft application. The process involves many steps and brings together much of the entire course's lecture material including: stress analysis, stress concentration application, failure theories, material properties, and the fatigue analysis that was recently covered in lecture. This fatigue exercise asked the students to develop a spreadsheet and produce specifically described graphical output using the fatigue theory presented in the textbook and explained in the lecture portion of the class. The students worked in teams of two and were given the entire three-hour lab section to complete the exercise. Since this was the last week of the quarter, no extensions were given. Grading of the exercise was relatively straightforward as the expected graphical output was specifically described although the spreadsheet format was up to the students. Unfortunately, no formal end of quarter survey was given to assess student outcomes or perceptions of the exercise during previous quarters.

The Fatigue MEA was developed as a different approach for reinforcing the fatigue analysis content of the course. In addition to giving the students experience in the application of fatigue theory to the design of a shaft, it was hoped that the students would gain a greater appreciation for the approximations and model formulation inherent in any fatigue failure theory. To do this, the students were not given a specific output format and were given additional test data for which a modification of the presented fatigue theory would be necessary to reconcile. In keeping with the principals of MEA formation, the teams (three students per team) were given a fictitious client who was in need of a graphical aid in shaft design. The students then needed to put themselves in the client's shoes and think about what output format would be beneficial. They were also given a set of shaft fatigue test data from the client (not actual data, but treated as such) for shot-peened shafts, a condition not treated in their textbook for predicting fatigue life. The students were required to incorporate this test data, as well as other changing design parameters such as shaft diameters and stress intensity factors, to make a fatigue life prediction tool for the client. Note that there are many possible ways to modify any of the several textbook fatigue theories to incorporate the effect of shot-peening. A copy of the actual Fatigue MEA is given in the appendix.

Assessment

The teams' performance on the MEA was assessed using two different scoring algorithms. The first metric is the Quality Assurance Guide that was proposed by Moore[3]. As shown in Table 1, This provides an overall assessment that measures "How useful is the solution (mathematical model) for the purposes of the client?"

Table 1. Quality Assurance Guide[3].

Quality Score	Performance Level
1	Requires Redirection
2	Requires Major Extensions or revisions
3	Requires only minor editing
4	Useful for the specific data given
5	Sharable or reusable

The second metric is a grading rubric (see Table 2) that was designed after Diefes-Dux, et al.[2] This rubric is based more on the technical content of the MEA product.

Table 2. Grading rubric for technical content[2].

Grading Rubric	
Criteria	**Points**
Input clear	1
Input complete	2
Fatigue Process	2
Labels	1
Graphic Output	2
Shot Peen Approach	1
Shot Peen Included	1

Finally, a student survey devised by Moore[3] was slightly modified and used to assess how well the students thought they performed as a team.

Results

The individual questions and the student responses to the survey are shown in Table 3.

Table 3. Responses to the Team Assessment Instrument[3] - mean (st dev)

Modified Likert Scale Survey 1= Strongly disagree, 2= Disagree, 3= Neither Agree nor Disagree, 4= Agree, 5 = Strongly Agree	
My team collaborated effectively to complete our assignment.	4.02 (0.80)
My contributions were appreciated by each team member.	4.23 (0.51)
I was able to count on my team members to contribute their fair share of what was required.	4.02 (0.83)
Our team used a process/method to hold each member accountable.	3.16 (0.99)
At any particular time, I knew what each member of my team's role was so I knew what to expect from him/her.	3.44 (0.98)
An outside observer would have concluded our team had an effective process to complete our assignments	3.40 (0.89)
The solutions of my team were better than what I would have done on my own.	4.08 (0.90)
This team helped me understand the material presented in this course.	3.98 (0.75)
I acquired skills necessary to contribute to working on teams in the future.	3.77 (0.92)
This team enhanced my academic learning.	3.85 (0.70)
This team showed me that teamwork is an important component to individual success.	3.90 (0.77)
I would prefer to work on a team rather than on my own.	3.73 (1.06)
This team showed me that I have much to contribute to a team.	4.10 (0.61)
Working on this team gave me a sense of individual accomplishment.	3.63 (0.79)
This team showed me how teamwork contributes to problem-solving.	4.06 (0.83)
This team showed me the importance of using clear goals to complete tasks.	3.96 (0.84)
My team made use of incremental goals (i.e., we set short-term goals) in order to do the assignment.	3.75 (1.01)
My input was used to set our team goals.	3.94 (0.70)
Overall, I thought being on this team was a very negative experience.	1.69 (0.76)
Our team did not function well as a team; we did not establish any process to hold one another accountable nor did I ever know what individuals were responsible for.	1.96 (0.93)
Overall the fatigue lab exercise was a valuable use of my time.	3.98 (0.87)

The scores for the grading rubric and the Quality Assurance Guide are provided in Table 4. Also note that six of the teams reported running out of time before they could finish the MEA.

Table 4. Grading rubric and Quality Assurance Guide results.

Team	Grading Rubric Scores (refer to Table 2)							Total Rubric Score	Qual Assur
	1	2	3	4	5	6	7		
A*	1	2	0	1	1	0	0	5	2
B	1	2	1	1	1	1	0	7	3
C	1	2	2	0	2	1	1	9	5
D*	0	2	2	0	2	0	0	6	3
E*	1	0	2	0	1	0	0	4	3
F	1	2	2	0	1	0	0	6	3
G	1	2	2	0	0	0	0	5	2
H	1	1	1	0	1	0	0	4	2
I	1	2	2	1	2	1	1	10	4
J	1	2	2	1	1	0	1	8	3
K*	1	1	1	0	0	0	0	3	2
L	0	1	1	0	0	0	0	2	2
M*	1	1	1	1	0	1	0	5	2
N	1	2	2	0	1	0	1	7	4
O*	1	1	1	1	2	0	0	6	3
P	0	0	0	1	0	0	0	1	1
Q	1	2	2	1	1	0	0	7	3
R	0	1	0	1	0	0	0	2	1
S	1	2	1	1	2	1	1	9	4

*Teams ran out of time during MEA.

Students were also asked "How would you change this exercise to improve it?" Many of the responses had to deal with the amount of time allotted for the MEA:

Either give more time or make it easy to complete in the allotted time
Then we could have time to understand the concept a lot better.

Although the instructor did recommend that the students complete their fatigue homework before coming to class, the majority had not looked at the material before coming to the lab.

It would have been beneficial to have had a better chance to practice some of the fatigue problems prior to the lab but alternatively, the lab was good practice for the homework. The main problem with my team was that I had started the homework while my partners had not.

If I had done the homework I would have been much better prepared, other than that it was very hard to complete in 3 hours but that is better than taking it home for finals week.
I think other groups would have had an easier time if they had done the homework (as you suggested); Maybe make the homework due closer to the lab date so that some students would have actually started the assignment.

One suggestion that will probably be implemented the next time the MEA is used was:
You could possibly give a short prelab question to try and get people up to speed. Another thing you could do is make one question from the homework a prelab question, so that people do not feel like they are being given extra work. You would just need to make the problem due at the beginning of the lab rather than with the rest of the homework.

Finally, many students did not seem to appreciate the open-ended nature of the MEA.
Have the instructor provide guidance other than "look in your book".
Show an example of what the final product should look like beforehand.
I would provide more information on what it is that you want students to actually turn in; by this I mean what you want plotted against what.
Better defined parameters as to what we are to do, although I guess that is part of the lab

Discussion

In general, the students thought the team experience was good (see Table 3). While they didn't necessarily use a process/method to hold each member accountable or establish well-defined roles, they did feel that they collaborated effectively to complete the assignment. They also agreed (average score 3.98) that the lab was an effective use of their time. It is also useful to examine the assessment scores. The Quality Assurance Guide (QAG) scores and the grading rubric had very similar results. All of the rubric scores below 6 had a score of 1 or 2 on the QAG. Similarly, the top three scores on the rubric had scores of 4 or 5 on the QAG. As would be expected, the teams who demonstrated good technical abilities also were able to provide meaningful results for the customer.

Modifying the existing fatigue lab exercise to make it an MEA was relatively straightforward. The handout to the student was largely in place, but had to be modified to take the form of a memorandum from a client. Removing the requirement of a specific graphical output was easy to do, although this made assessment more difficult. More time was necessary to develop realistic fatigue data for shot-peened shafts that allowed the students to explore how existing fatigue theory might be modified to accommodate the effects. The overall results were positive. Many students asked insightful and relevant questions regarding the incorporation of shot-peen data. The students were less effective at developing a plan for creating a graphical output useful for the client. They seemed either unwilling or had difficulty in placing themselves in the role of the client, and had trouble understanding what they would want to aid in the design of shafts. Lastly, the exercise seemed to take the majority of students more than the three hours to complete. Because an overriding goal for this exercise was to have the students finish in the allotted time, this was a failure in scoping the exercise properly. This problem was partially due to the timing of the exercise with respect to the lecture and homework assignments on the fatigue theory. As suggested by one of the students, having fatigue theory homework due prior to the laboratory meeting may solve this issue. As implemented in the fall, the students had not practiced applying the theory to textbook problems; therefore, they spent a considerable portion of the lab time reviewing notes and reading the text to understand how to apply the theory.

Conclusions and Recommendations

Setting up the MEA as a modification to an existing close-ended assignment was relatively easy once the idea of having the students arrive at the same "correct" answer was abandoned. This is the type of problem that most students will face in their careers. The majority of students seemed to intuitively understand the importance of modifying proven theory to incorporate new data. Some students did resist this, which was useful in opening up a dialog concerning the practical nature of engineering judgment and theory.

In the future, we hope to modify the MEA to provide a more manageable exercise for our students. The motivation of having an "outside customer" prepares the students for assignments they may encounter in their careers, but the current assignment was too long for them to complete in class. After assessing the benefits of MEAs, we hope to develop additional exercises that integrate physical laboratories that enhance learning.

References

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2. Diefes-Dux et al., "A Framework for Posing Open-Ended Engineering Problems: Model Eliciting Activities," *34th ASEE/IEEE Frontiers in Education Conference,* October 2004.
3. Moore et al., "The Quality of Solutions to Open-Ended Problem Solving Activities and its Relation to First-Year Student Team Effectiveness," *Proceedings of the 2006 American Society for Engineering Education Annual Conference & Exposition*, June 2006.
4. Hamilton, E., et al., *Model-Eliciting Activities (MEAs) and Their Assessment as a Bridge Between Engineering Education Research and Mathematics Education Research.* Journal for Engineering Education, in review.
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APPENDIX: Fatigue MEA

To: Mechanical Design and Analysis Associates (MDAA) (a.k.a. your team)
From: Durable Shafts Are Us Company (DSAUC)
Re: Custom Shaft Design Computer Code

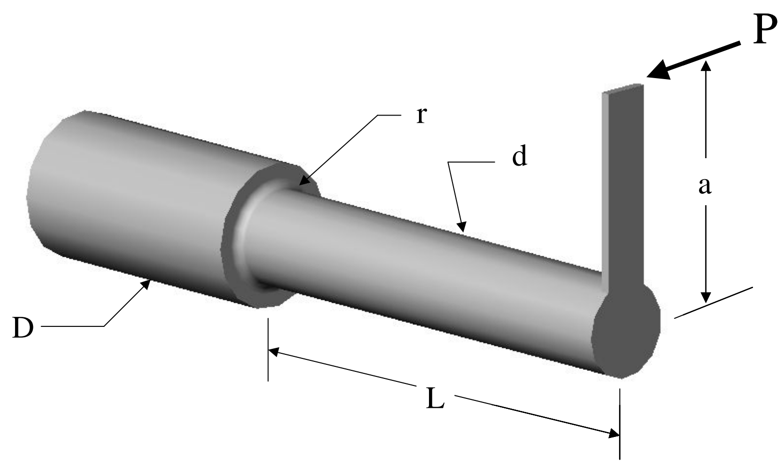
Purpose: MDAA (your team of three) has been hired as consultants to design and develop a user friendly software aid to be used in shaft design for the DSAUC. DSAUC has been having problems understanding how their shot-peened shafts fail in fatigue and would like to have a standard EXCEL spreadsheet that will aid its designers in shaft design using consistent shaft modeling. DSAUC is hiring you due to your expertise in the area of design for fatigue. They would like your code to generate design charts to aid further in their design decisions regarding shafts subject to fluctuating loads. To better understand their shot-peened shafts, DSAUC has tested several samples. The results are shown in the table below.

Introduction:
DSUAC designs different gear reduction units that transmit varying torques at various reduction ratios. The fatigue properties of the shafts can be improved through the shot-peening process. In this process small steel balls are shot at the shafts. The impact produces compressive residual stresses near the surface of the shafts in an attempt to improve fatigue life. All units have an output shaft that is gear driven . Usually the output shaft drives a time varying torque that varies at a frequency of 1 cycle of loading per 1 revolution of the shaft. A simplified model of one gear tooth and the output shaft is shown below. Based on your knowledge of fatigue covered in ME328 to date, and the results of MDAA's test data you will create graphical output (charts?) showing the effect of dimensional changes on fatigue life of the shafts. DSUAC designs many shafts that look like the one below. Testing shows that the critical section for fatigue on the shaft is at the diameter discontinuity with the radius r shown below. DSUAC uses 4130 Normalized steel.

The following properties should be considered fixed for this design aid:

D = 3 in	Alternating Load, P_a = 500 lb
L = 10 in	Mean Load, P_m = 250 lb
a = 5 in	Room Temperature
	99% Reliability
	Ground Surface Finish

The parameters that DSAUC typically varies are:
- Shaft diameter: 1.20 in $\leq$ d $\leq$ 2.50 in
- Notch radius: 0.05$\leq$ r/d $\leq$ 0.25
- Radius of Gear: 4$\leq$ a$\leq$ 8 in



DUAC Testing Results

Tests were conducted using machined shafts with D = 3 in, d = 1.2 in, r = 0.06 in, a = 5 in. Loads were varied as shown in the table below.

Pm (lbs)	**Pa (lbs)**	**Cycles to Failure**
55	290	2.35×10^6
160	240	$>1.0 \times 10^7$
425	210	9.24×10^5
530	140	$>1.0 \times 10^7$
560	120	3.21×10^6

Deliverables:

Prepare a spreadsheet that allows the DSAUC engineer to visually see how the factor of safety is affected by different values of r/d, and D/d. The contract expires in two hours and 50 minutes at which time you will turn in an electronic copy and a printout of your spreadsheet to the DSAUC representative. Be sure to include your names and lab section number on the spreadsheet along with a short description of your modeling of the effect of shot peening.

Hints:

- Section 6-14 describes the procedure for handling fatigue estimation with combined loads.
- Table 6-8 defines the Safety Factor for combined mean and alternating fatigue loading.
- As a team, approach this problem using a standard design process and assign individual tasks when appropriate.

DSAUC Suggestions:

1) Define common variables at the top of your spreadsheet (for example, D, L, a, S_U, S_e', P_m, P_a, k_c, k_d, k_e, etc…).
2) Make the input area on the sheet obvious and clearly indicate what should be inputted.
3) Any graphical output should be shown on the same sheet as the input
4) Any calculated tables should not be on the main sheet.
5) Make liberal use of labels.