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Work in Progress: Leveraging Inquiry-based Simulated Laboratory Exercises in a Virtual Classroom Environment

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Leveraging Inquiry-Based Simulated Laboratory Exercises in a Virtual Classroom Environment

Track Selection: Experimentation and Laboratory-Oriented Studies Division

Abstract

We report on the implementation and impact of virtual laboratory modules in a specialized engineering course titled 'Nondestructive Evaluation of Flaws' offered virtually in Fall 2020. The proposed curriculum changes aim to address two key challenges associated with teaching this course: (i) students' difficulty in learning the theoretical principles behind disparate test methods taught in one semester and (ii) students' widely different backgrounds and preparations. The virtual laboratory experiences include hands-on simulation of various test scenarios using a commercial software. This is accomplished by student groups meeting in break-out rooms. In addition, video demonstrations are used to show operational principles of each testing method. In the former case, the students are asked to first predict the outcome of a test scenario based on their understanding of the theory, run simulations and then discuss the simulation results in light of their initial predictions. In the latter case, the videos are shown once before teaching each test to introduce the method and inspire students' curiosity. The video is shown a second time after teaching the test for students to gauge their learning (since the first screening) and develop (partial) test protocols. The assessment includes pre- and post-surveys as well as quiz problems on the test fundamentals. The student performance when answering targeted quiz questions shows a significant increase in their learning of fundamental physical principles. The results of the post-survey are overwhelmingly positive alluding to a positive course experience by an overwhelming majority of students, independent of their background and initial interest in the course (as determined in a pre-survey). We conclude that although a virtual laboratory cannot replace an actual hands-on laboratory experience, it seems to improve student learning and class experience even in a virtual class environment. More careful assessments in future offerings of the class are necessary to better quantify the impact of the virtual laboratory implementation.

Introduction and Background

The course 'Nondestructive Evaluation of Flaws' is a senior-level technical elective cross-listed by two departments at [university] (Engineering Science and Mechanics and Materials Science and Engineering). The course draws in about 30 students from diverse engineering and scientific disciplines such as Engineering Science and Mechanics, Materials Science and Engineering (MATSE), Industrial Engineering, Biomedical, Nuclear and Mechanical Engineering. This is a specialized course, which provides a survey of standard nondestructive evaluation (NDE) techniques. American Society for Nondestructive testing (ASNT) defines NDE as "the process of evaluating, testing, or inspecting materials, components or assembles for discontinuities or differences in (material) characteristics without destroying the serviceability of the part of system [1]." The reason the course attracts a diverse body of students is that NDE is being increasingly used in various industries for process control, flaw diagnosis and failure prognosis. There are many different NDE techniques including [2] liquid penetrant testing (PT), magnetic particle inspection (MT), Eddy current (ET), radiography (RT) and ultrasonic testing (UT). Each technique relies on distinct physical principles ranging from capillary action (PT) to wave physics (UT), which are essential to the understanding of the test operation, data interpretation and potential applications. The course provides the theoretical foundation, operating principles and applications of each technique. The learning objectives include: communicate the physical principles behind each of the NDE techniques (introduced in the class) to a researcher, an engineer or a stakeholder from industry; demonstrate understanding of each method's physics by connecting the physical principles to the applications; compare various plausible NDE techniques for common industrial applications; given an application, identify one or more appropriate NDE technique(s) by providing convincing scientific reasoning and justification.

Teaching 'Nondestructive Evaluation of Flaws', an all-around course in NDE, using the traditional lecture-based methods is challenging because: (1) each NDE method is based on a different physical principle; it is difficult for the students to grasp all the different principles and methods one after the other within the short 15-week timeframe of one semester, and (2) the class is highly heterogenous; the students have very different backgrounds and preparations. Students with little or no preparation have a lot of difficulty understanding the physics and connecting the physical principles to the methods and potential applications within the short timeframe each method is discussed.

To address these challenges, we augment the (virtual) class by *virtual laboratory* sessions in order to reinforce student understanding of the physics and operation of select NDE techniques (ET and UT). Simulation-based virtual laboratories have long been used to increase learning in engineering courses. For example, Kukreti *et al.* [3] developed simple simulation tools to teach fundamental concepts of 'Strength of Materials', a core engineering course while Derks *et al.* [4] combined actual and laboratory modules in teaching 'Structural Analysis', a Civil Engineering course. Here, the virtual laboratory environment is created in two distinct forms: (1) hands-on interactive NDE testing scenarios enabled through numerical modeling and simulations and (2) videos showing the field operation of a particular NDE technique. Unlike the previous studies, the virtual laboratory is designed using a professional (industry-oriented) simulation software (educational version of CIVA from EXTENDE [5]). The software provides realistic visuals and graphics to create an interactive virtual NDE testing environment, where the students can simulate and analyze different test scenarios. The video screenings include demonstrating videos showing NDE professionals conducting a test and interpreting the results. Importantly, the course is delivered virtually, which makes the implementation very different from that in an in-person classroom setting.

This paper provides a detailed discussion of the virtual laboratory modules added to 'Nondestructive Evaluation of Flaws'. In addition, we report how the changes impacted the student learning in Fall 2020 compared to Fall 2019, when the delivery was strictly lecture-based. Finally, we discuss 'lessons learned' and modifications planned for the next offerings of this class. Our overall assessment results indicate a positive impact of the virtual laboratories on student learning. We conclude that although a virtual experience does not replace an actual hands-on laboratory experiment, it is a powerful educational tool that enhances student learning and class experience, especially in a virtual classroom setting as reported also by Vasiliadou [6].

Virtual Laboratory Modules

The course 'Nondestructive Evaluation of Flaws' was offered in a virtual mode (synchronous) in Fall 2020. Compared to the offering in Fall 2019 (in-person including several laboratory visit and demos), two types of virtual laboratory experiences were included in Fall 2020: (1) hands-on interactive testing scenarios enabled through a commercial numerical simulation software and (2) video demonstrations of the field operation of a particular NDE technique. The following provides details on either laboratory module.

Simulation-based virtual lab

These virtual laboratories are designed using a professional numerical modeling software (educational version of CIVA from EXTENDE [5]). The software provides realistic visuals to create an interactive virtual testing environment for ET, RT and UT. Therefore, using the software, the students can simulate and analyze different sensor responses and/or test scenarios. We use CIVA in teaching ET and UT, two of the methods that require more in-depth understanding of the physical principles: electromagnetics in case of ET and wave physics in case of UT.

Each module (ET or UT) includes several in-class group exercises organized through zoom breakout rooms. With only 5 CIVA educational licenses available, the 28 students in the class are divided into 5 groups of 5-6 students. Due to the software requirements and licensing issues, the software is installed on 5 workstations, one workstation per group. One of the students in each group (rotating group leader) remotely connects to the designated workstation for the group, shares their screen with the others in the break-out room to complete the exercise. As will be noted later, the limited number of licenses, virtual nature of the class and required steps to access the software posed some challenges to the smooth conduct of the class.

For each NDE technique simulated (ET or UT), two sets of exercises are designed. The first set involves simulating and exploring the sensor response for different relevant test parameters such as sensor (probe) size and characteristics such as frequency and type (absolute vs. differential) as well as test material properties (see the example for ET in **Figure 1**). In this exercise, the students are first asked to *predict* the sensor (probe) response (based on what they have learned in the lectures and reading materials) and then calculate the response using the simulation software (**Figure 2**). Afterwards, the students are asked to analyze the response in light of their initial predictions and reflect on any mismatch. In this first exercise, the students only study the probe physics and not the probe interaction with a flaw, which will be explored in the second exercise. Note that the students are explicitly asked not to modify their initial predictions when submitting their work. They are told that a wrong initial guess does not affect their exercise grade as long as the discussion clearly identifies the error in light of what they observe in the simulations.

Exercise #1: Use **ET field simulation** to calculate **'electric field'** for an **absolute probe** on **aluminum** and **stainless steel**

Specimen geometry:
100 mm x 100 mm x 5 mm (planar)

Probe characteristics:

Inner diameter = 3 mm
Outer diameter = 5 mm
Height = 3 mm
N of turns = 100
Liftoff = 0.4 mm
Frequency = variable

1) How do you think the electric field changes with depth?

Use your simulation results to verify your answer.

2) How the response of the sensor would be different on aluminum vs. stainless steel?

Calculate the response for probe frequencies ranging from 1 kHz-100 kHz & liftoff ranging from 0.001 mm-1 mm.

Does the response match your expectation? Discuss.

Figure 1. *The first exercise for ET simulation asks the students to first predict the sensor (probe) response and then calculate the response. Afterwards, the students are asked to reflect on their initial predictions.*

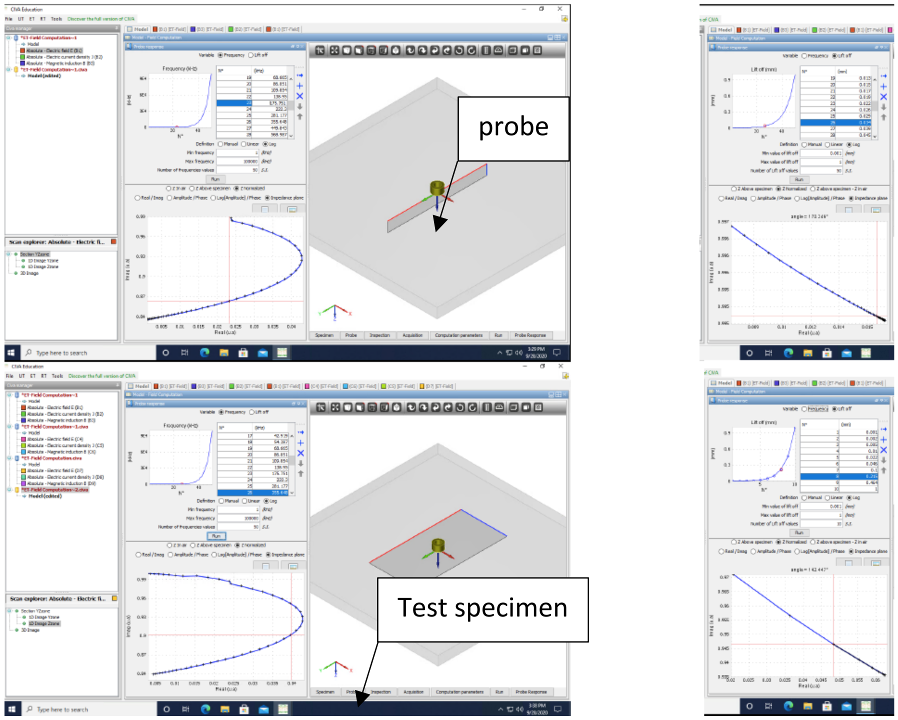


__Figure 2__. An example of the first exercise for ET simulation, where the probe response for a range of frequencies and liftoffs is calculated (the probe and the specimen are marked).

The second exercise is designed differently for ET and UT. For ET, a part of the exercise is exploratory. First a test scenario is defined by providing basic geometrical and material properties of the specimen and sought flaw as well as probe characteristics. Next, the students are asked to run a parametric study and observe/document the influence of various flaw parameters (location and size) and probe characteristics on the ET response. Finally, the students are asked to discuss their results in light of lecture notes and class readings. This exercise is motivated by observing the difficulties the students have in understanding how different flaws change ET response. (see **Figure 3**).

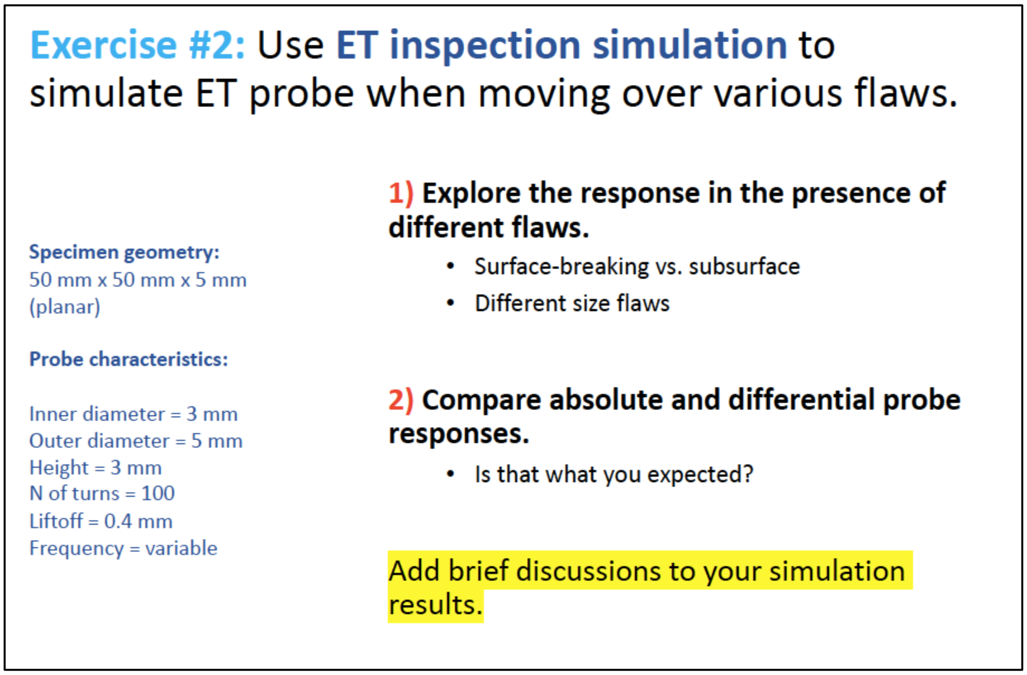


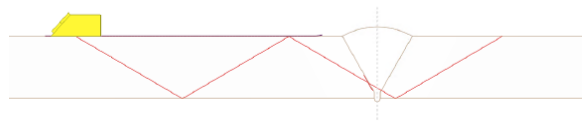
Figure 3. *The second exercise for ET simulation is of exploratory nature. However, the students are asked to discuss their simulation results in light of theory.*

For UT, the exercise is divided into two activities: Activity #1 and #2. Activity #1 encourages the student groups to form a hypothesis for the NDE simulation in Activity #2 and recall important aspects from lectures (**Figure 4**). Then, the students use the software to create a test specimen of given material properties and geometry containing a flaw of pre-defined characteristics (provided by the instructor). Next, the students have to *design* a probe (according to their calculations in Activity #1) and the corresponding test procedure (e.g., where to place the probe and how to move it to detect the flaw) (**Figure 5**). Then, they study the effect of flaw on the sensor response interactively (for example by moving the sensor toward the flaw and away from it) and analyze the response to see if they can detect/size the flaw decide and decide whether they have designed the appropriate probe and testing scheme. Finally, they reflect on their observations.

Activity #1: Use your knowledge of UT to answer the following questions <u>before</u> running the CIVA simulations.

1) Assume that you have three angle-beam probes: 45-degree, 60-degree and 70-degree.

Which one do you think would be most suitable for this inspection task? Explain and justify your answer.



2) Once you choose the appropriate probe, how would you size the flaw? Explain your answer with a schematic.

Figure 4. *The second exercise for UT simulation involves a test design. Before running the simulations, the students are asked to form a hypothesis about the test scenario (type of probe).*

Activity #2: Run <u>UT inspection simulation(s)</u> to investigate the validity of your answers in Activity #1.

1) Is the probe you had suggested in Activity #1 appropriate for detecting the flaw?

If yes, support your answer by showing A-scan(s) and B-scan of your simulated UT inspection.

If no, use CIVA to find a more appropriate probe. Show the corresponding A-scan(s) and B-scan. Note that you don't need to change your answer in Activity #1.

2) Move the probe away from the flaw (along the y-axis) to a location, where the weld has no flaws (y = 25 mm). Compare the A-scan(s) and B-scan in this location to those obtained in (1). Describe your observations.

3) By moving the probe along the x-axis and showing the corresponding A-scans, demonstrate the validity of the sizing method you proposed in Activity #1.

Figure 5. *The second exercise for UT simulation involves a test design.*

Video demonstrations

These virtual laboratories are conducted using video demonstrations of NDE techniques (PT, MT, ET and UT) by a professional. In case of ET (**Figure 6**) and UT, the video is played twice. The first screening precedes the discussion of ET (or UT) in the class while the second time is after the respective module (ET or UT) is taught. After the first screening, the student groups meet in break-out rooms in Zoom and discuss what they understood from the test procedure and results. Each group reports back to the class their understanding together with the technical terms they heard. The second screening is at the end of the discussion of the module asking the students to watch the video, meet in break-out rooms and write the corresponding test protocol. The students are asked to gauge their understanding of the method compared to the first screening and in relation to the method theory.

***Figure 6.** An example of video demonstrations (ET crack detection) [7]*

Assessment

The following questions guide the assessment of adding virtual laboratories to the course:

- Did the student learning of ET principles increase?
  - Could they relate the theory to practice and understanding the working of the method (ET)?
- Did the student learning of UT principles increase?
  - Could they relate the theory to practice and understanding the working of the method (UT)?

- How did the virtual laboratories impact the overall course satisfaction and engagement in a virtual class?

Assessment Methods

In order to assess the impacts of the virtual laboratories described above, a number of assessment methods are employed:

- A short pre-survey and a post-survey are conducted. The pre-survey evaluates students' interest in NDE and their familiarity with different methods. In post-survey, the students are asked to provide their overall satisfaction with modules that include virtual laboratory activities compared to those without. Finally, they are asked to evaluate their interest in NDT and its relevance to their future career.
- Targeted quizzes that evaluate the student learning of ET and UT principles and operations and compare the results with the previous offering of the class in Fall 2019, where no virtual or physical laboratory is implemented. The Fall 2019 offering included laboratory visits and demonstrations, but no simulation-based or hands-on experimentation.

Assessment Results and Discussion

The following summarizes the assessment results:

- Twenty-six (26) students (out of 27) participated in the pre-survey. Ten (10) students alluded to some prior exposure or particular interest in NDE techniques. The rest took the course to fulfil a technical elective or minor requirement.
- The overall student satisfaction with the course (virtual, Fall 2020) was overwhelmingly positive with the student evaluation of course significantly improved compared to the previous offering (in person, Fall 2019) (see **Table 1**).
- To assess the overall course satisfaction among the less prepared students, we consider the overall course rating among Materials Science and Engineering (MATSE) students who tend to have less prior knowledge of the course material especially the physical principles behind certain methods. As shown in **Table 2**, the overall rating in Fall 2020 shows a significant improvement over Fall 2019.

Table 1. *A comparison of student rating when answering 'Rate how well this course increased your understanding of the course topics?'*

Rating*	**1 (lowest)**	**2**	**3**	**4**	**5**	**6**	**7 (highest)**
Fall 2019	0 (0.0%)	1 (3.0%)	2 (7.0%)	6 (21.0%)	4 (14.0%)	11 (38.0%)	5 (17.0%)
Fall 2020	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (4.2%)	2 (8.3%)	3 (12.5%)	18 (75.0%)

* The University uses a 1 to 7 rating scale with 1 representing the lowest rating and 7 the highest.

- Despite the virtual nature of the class, the attendance remained high throughout the semester. A number of comments pointed out the positive impact of break-out rooms in remaining engaged during the class throughout the semester. For example: "I thought the breakout rooms were very helpful. It allowed us to interact and forced us to think critically about the course material. I also liked that we had to summarize each technique after we finished."
- Based on a comparison of quiz grades between the two offerings of the class in Fall 2019 and Fall 2020, the students' learning of physical principles appears to have increased. A total of 28 students took the ET quiz in Fall 2019. The average score was 73% ranging from 50% to 90% with a standard deviation of 11.29%. In Fall 2020 when the virtual laboratories were implemented, the average quiz score was 91%. The grades ranged from 40% to 100% with a standard deviation of 16.05%.
- Comparing the students' answers to specific quiz questions on ET and UT principles, the improvement is even more pronounced. For example, 23 out of 27 students (85%) answered the question "When placed on a non-ferromagnetic conductive test specimen, the inductive impedance of an Eddy Current (EC) probe ___________________." correctly, compared to only 21% in the previous offering of the class in Fall 2019.
- In the post-survey, a few students noted issues with limited software licenses (only one person in a group could have hands-on experience with CIVA at a time) and technical difficulty with CIVA (crashes, etc.). However, the students themselves acknowledged that some of the technical difficulties were due to the virtual nature of the class.

Table 2. *A comparison of MATSE student rating when answering 'Rate how well this course increased your understanding of the course topics?'*

Rating*	**1 (lowest)**	**2**	**3**	**4**	**5**	**6**	**7 (highest)**
Fall 2019	0 (0.0%)	0 (0.0%)	1 (8.0%)	2 (17.0%)	3 (25.0%)	4 (33.0%)	2 (17.0%)
Fall 2020	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (17%)	2 (33%)	3 (50%)

* The University uses a 1 to 7 rating scale with 1 representing the lowest rating and 7 the highest.

Conclusions and Implications

Although a virtual laboratory cannot replace an actual laboratory, it may still help students grasp difficult-to-understand subjects. Based on student feedback and targeted quiz grades, the implemented virtual laboratories seem to have improved the students' learning of the method physical principles. More rigorous assessment strategies are required to better quantify the impact of virtual laboratories on students' understanding of physical principles for example, knowledge surveys before or after a virtual laboratory session and asking targeted question about virtual laboratory experiences in post-survey. The student feedback will be used to improve the instructional material and exercises for future offerings of this class.

Acknowledgements

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