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CONCEIVE-DESIGN-IMPLEMENT-OPERATE (CDIO) EXPERIENCE IN A
SOPHOMORE-LEVEL AERODYNAMICS COURSE

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Integration of a Conceive-Design-Implement-Operate (CDIO) Experience in a Sophomore-Level Aerodynamics Course

Abstract

The CDIO Initiative is a partnership for improving engineering education through a multidisciplinary hands-on curriculum, real-world applications, and communication skills. The formation of the CDIO Initiative was a response to feedback from industry surveys which communicated that although today’s engineering graduates are technically competent, they generally need one to two years of additional training before they are ready to function as engineers. Some of the common weaknesses cited are communication skills, including graphics, the ability to work in teams, and design skills. This paper will present a plan for a five-semester concurrent engineering design sequence, as well as an expanded use of design experiences in core engineering courses. Students will present an aerodynamics CDIO project that enhances their understanding of the effect of planform shape on finite wing performance and gives them additional experience with solid modeling, CAD/CAM, and analysis tools. Of particular interest will be an airfoil that is modeled after a humpback whale flipper and has bumps on the leading edge called tubercles.

I. Introduction

The CDIO Initiative (2006) started at M.I.T. and has gained national and international partners. The vision statement for CDIO states, “The CDIO Initiative offers an education stressing engineering fundamentals, set in the context of the Conceiving-Designing-Implementing-Operating process, which engineers use to create systems and products.” Unlike project-based education, which fills in content as it is needed to complete a particular project, the CDIO approach is to integrate and weave CDIO experiences throughout a more traditional content and skills-based curriculum.

The CDIO Website has a great deal of information about the CDIO philosophy of education. It includes the 12 CDIO Standards that, “define the distinguishing features of a CDIO program, serve as guidelines for educational program reform and evaluation, create benchmarks and goals with worldwide application, and provide a framework for continuous improvement.” It also includes the CDIO Syllabus Report, which gives guidance on creating a CDIO program, and the CDIO Syllabus (http://www.cdio.org/Cond_syl.html) to help instructors develop learning objectives and detailed content.

II. How Much CDIO is Enough?

Many engineering programs have moved a design experience into the freshman year; however, in some programs students do not have a significant design experience again until the senior year. The skills involved in the design process (solid modeling, analysis, simulation, CAD/CAM, rapid prototyping, testing, systems integration, documentation, and team work) should be learned, developed, and practiced throughout the undergraduate experience.
In the area of documentation, Professor Mario Castro makes some relevant points in his paper, *The Role of Engineers in the Creation of Engineering Drawings--Past, Present and Future (2004)*. “The number of drafting technicians peaked in 1980 and has been steadily decreasing since then.” Professor Castro states that, “most engineering organizations now expect engineers to perform tasks previously assigned to designers, and to do them without the benefit of lengthy on-the-job training, while simultaneously learning to apply other traditional engineering skills such as analysis and project management.” He also points out that, “the widespread use of solid modeling has not eliminated the need to use drafting standards and conventions properly because today’s CAD database contains more information than before, and it will be the engineers creating early concepts who will also specify all the information required for detail design.” Professor Castro concludes that, “engineering students will benefit if drafting skills continue to be developed in their upper-level courses in materials, manufacturing and design synthesis.”

Developing documentation skill takes time and practice and is just one of the areas that the CDIO philosophy tries to address. The move to a CDIO program also requires radical changes in the delivery of the curriculum.

### III. Transitioning from an AS to a BS Program

Daniel Webster College (DWC) has offered two-year transfer programs in aeronautical engineering and engineering science for many years. In 1996, after attending an NSF Concurrent Engineering Design Workshop at the University of Texas at Austin led by Ronald Barr and Davor Juricic, we began developing a three-semester concurrent engineering design sequence for our two year program. This sequence took about six years to fully develop and implement and the process is described in *Implementation of a Three-Semester Concurrent Engineering Design Sequence for Lower-Division Engineering Students (2005)*. The design sequence was so successful in helping to recruit, motivate, educate, and retain students that four-year programs in aeronautical engineering and mechanical engineering are now being implemented. The junior year is being offered in aeronautical engineering for the first time this fall.

In May 2006 DWC was accepted as a CDIO partner. DWC joined the CDIO initiative because we know that this educational philosophy works with engineering students and as we develop the junior and senior courses for our new programs and continue to modify our lower-level courses it will be of great benefit to us to examine and discuss the best practices already developed by the CDIO partners.

CDIO will strongly influence our programs as we seek to apply the 12 CDIO Standards and the CDIO Syllabus to our new and existing courses. Although we have already applied some of the general principles, CDIO provides a well thought-out, well-organized template for implementation.

Both of our new engineering programs are still under development and will continue to change significantly over the next few years. The course sequencing in our current catalog can be viewed online at (http://content.dwc.edu/pdf/catalog/currentcatalog.pdf). Both BS programs contain five-semester design sequences. We have also increased the number of credits for the first three design courses and for many of the other engineering courses from 3 to 3.5. These
courses will meet four hours per week instead of three hours. The purpose of this increase was to allow time for more in-class student presentation opportunities and hands-on and project work directly related to the course material as it is being studied. Design class section sizes are capped at fifteen and engineering section size capped at twenty so that these experiences can be effective. All five of the design courses will be team taught with humanities faculty who will provide instruction and evaluation of written and oral presentation skills and application of ethics and societal impacts of engineering.

One of the ways that CDIO has already affected our curriculum development is in the redesign of our Engineering Design II course, which is taken in the spring semester of the freshman year. In recent years, Engineering Design II included five weeks of advanced solid modeling techniques, followed by ten weeks of C programming taught in the traditional way by faculty in the Computer Science department. During the ten weeks of programming students would also continue to work on their design projects, which were primarily mechanical in nature. However, although we have excellent computer science faculty, the students in general were dissatisfied with the programming part, not seeing how it applied to what they were doing with their design projects.

For the spring 2006 semester, Professor Craig Putnam, one of our engineering professors, redesigned the programming part of the course. With Professor Putnam’s redesign, the students receive an electronics box that includes a breadboard, PC board, chip, switches, relays, LEDs, and LCD display, etc. The students build and debug a microprocessor device to which they can download their C code for testing. Each time they learn a new topic in C, they can test it in their devices. The microprocessor device they build will then be directly integrated into their semester design project and can be saved for use in future design projects. We have already seen a dramatic increase in interest among the engineering students for this part of the course.

Suggestions offered by faculty members from other CDIO institutions have also resulted in the following adjustments to the delivery of the design sequence:

- Because freshmen are generally inexperienced in group project work and project management, the team size is limited to 3 students in the first design course and four students in the second. This makes it easier for the students to meet and reduces the likelihood of having members who aren’t contributing. Once the students gain some familiarity with small groups it is useful for them to experience working with a large group, so in the upper-level design courses the group size is allowed to expand depending on the scope of the project.
- Also, the design projects used in the first two courses are defined by the instructor and clear milestones are established for the students. The focus is as much on the design process as it is on the design project. In the upper-level design courses the student teams submit their own project proposals and set their own milestones.

Syllabi for the first three design courses can be found at: (http://faculty.dwc.edu/bertozzi/). The most recent design project descriptions and assessment milestones can also be found at this site. The two senior capstone design classes are still under discussion and development at this time. The syllabi for these courses will be put on our Website when they are ready.
IV. Student Perspectives

One way to measure the success of the program is to evaluate how easily students—who have been educated and exercised with engineering graphics tools and CNC machines—adapt to real-world environments. Currently, four Daniel Webster College students are pursuing their aeronautical engineering degrees full time as well as working for a local custom thin film circuit and interconnect manufacturer. All four of these candidates manufacture product on the weekends and two of the candidates also support the engineering department with value added project work between classes. Equipment and processes cannot be disclosed for reasons of business confidentiality. However, several of the machines operate using software familiar to the students participating in the Daniel Webster College five-semester design sequence.

Two examples will be discussed in order to present the benefits of engineering graphics software in an engineering curriculum. The first example is the basic idea of teaching students how to read and interpret drawings. These students have been exposed to drawings in the curriculum from day one. This enables them to walk right into a workplace and understand what the drawing is communicating. The correct revision of the drawing, the measurement system being used, dimensioning, tolerances, detailed and section views are all items that the student checks for, and in so doing generates questions regarding how to properly manufacture the product as opposed to essentially learning a new language. Also, because there is a huge customer base, students have been given the tools to teach themselves how to translate the diverse style of drawings.

The second example considers one of the machines in the factory which utilizes software environments that students were already familiar with from their curriculum. The engineer who performed the necessary training regarding the operation of the machine was not only amazed at how fast they picked concepts up, but also the level of questions they were asking. It was clear that the students wanted to learn the theory of how the machine worked, not just run the machine. The operator of the machine must be able to use and modify the product in a CAD software environment and then export the information to virtual tool path and NC code generation software. Although the brands of software packages used on the job are not the same, these students had already used modeling software and readily exported the information to virtual tool path and NC code generation software to operate a CNC milling machine at the DWC campus for curriculum-based project work. Instead of being taught how to use the software, the students asked what functions are required to complete the task. They have been given the tools to successfully teach themselves in a real-world environment.

As a result of these examples, the employer was able to bring an outsourced manufacturing process in-house, reducing cycle time and costs. In addition to the previously mentioned equipment, the small team of students has learned how to operate similar equipment and continue to work during the weekends in a self-supervised manner, keeping key product flowing as well as working in a technical environment. These basic to in-depth examples show the positive advantages to educating and exercising students with engineering graphics tools and CNC machines. In this case, the students are manufacturing operators. However, one day, when they purchase and support equipment or even communicate with a subcontract manufacturer, they will have a much more in-depth understanding of what it takes to get the product to the
customer. More importantly, the engineering graphics tools necessary for success have been incorporated into the foundation of their education.

V. CDIO Aerodynamics Project

This section discusses an aerodynamics CDIO project that enhances student understanding of the effect of planform shape on finite wing performance and gives them additional experience with solid modeling, CAD/CAM, and analysis tools. As was mentioned earlier, a majority of the engineering courses have been changed from 3 to 3.5 credits. Part of the reason for doing this was to provide for additional project work beyond the design courses. The students are learning how to use modeling and design tools in the design sequence, and benefit from additional experience using these tools in their other engineering courses.

In the aerodynamics course, students do wind tunnel testing with a wing that has a rectangular planform, 10 inch span, 2.5 inch chord, and a NACA 0015 airfoil section. They have also modeled and machined a linearly tapered wing and an elliptical wing that have the same airfoil section, span, planform area, and aspect ratio as the rectangular planform wing. The tapered wing must be designed with a taper ratio that will produce the minimum possible induced drag for a tapered wing. Theoretically, the elliptical planform wing should have the minimum induced drag of any planform shape. Once the wings are made they can be tested in the wind tunnel and their lift coefficient and drag coefficient curves compared to the theoretical predictions.

In addition to the three planforms just described, a team of students also wanted to model, build, and test a wing with tubercles. Humpback whales work together in teams by blowing bubbles as they circle schools of fish. They swim in tighter and tighter circles until they have corralled a dense column of fish and then take turns swimming up through the center of the column while swallowing tons of fish per pass. Humpback whales are unusual among baleen whales in their ability to make the sharp turns necessary for this maneuver. They have very high aspect ratio flippers which have large bumps or tubercles on the leading edge. Usually when you see physical features such as this in nature (see Figure 1), they are there for a reason and various studies have been done to investigate the effect of the tubercles on the aerodynamic efficiency of the flipper.

One such study was done by Professors Miklosovic and Murray from the Naval Academy, Professor Howle from Duke University, and Professor Fish from West Chester University. Their paper is entitled, Leading-edge Tubercles Delay Stall on Humpback Whale Flippers (2004).
They used a NACA 0020 airfoil in their study due to the similarities with the actual Humpback whale flipper and found that the flipper with tubercles performed better at higher angles of attack and that the addition of tubercles on an idealized humpback whale flipper delays the stall angle by approximately 40% while increasing lift and decreasing drag.

The DWC student team used a NACA 0015 airfoil shape and added tubercles to a rectangular planform. To create the solid model of the tubercle wing a design table containing the NACA 0015 airfoil data was used to control sketches on various work planes as shown in figure 2.

CAD/CAM software was used to create the tool paths needed to make the part. The wings shown in Figure 3 were made out of blocks of Lexan. Machining the top surface is straightforward. To machine the bottom surface is more difficult because there are no flat surfaces to hold on to. To solve this problem the students first machine a negative (which is shown in Figures 4 and 5) and put in some tapped holes for tie down screws. Two holes are reamed for dowel pin insertion in order to provide for very accurate positioning.
The finished wings were tested in our wind tunnel at a Reynolds number of 106,000. Published data is available for the NACA 0015 infinite aspect ratio wing. By applying finite wing theory to this 2D data the theoretical 3D lift and drag coefficients were generated for both the rectangular planform and for the elliptical and tapered planforms. Due to the taper ratio chosen, the theoretical coefficients for the elliptical and tapered wings were virtually identical.
These comparisons are shown in figures 6-9. There are no efficiency factors available for the tubercle wing, so no theoretical 3D coefficients could be generated from the 2D published data for this planform. The wind tunnel results were reasonably close to the theoretical curves for the rectangular, tapered and elliptical planforms. It is interesting to note that the elliptical planform performed significantly better than the tapered planform (Figure 8). As was stated earlier, theory predicted that these two should be almost the same.

Figure 6. Wind Tunnel and Theoretical Lift Coef. Comparison for the Rectangular Planform

Figure 8. Wind Tunnel and Theoretical Lift Coefficient Comparison for the Elliptical and Tapered Planforms

Figure 7. Wind Tunnel and Theoretical Drag Coef. Comparison for the Rectangular Planform

Figure 9. Wind Tunnel and Theoretical Drag Coefficient Comparison for the Elliptical and Tapered Planforms
The wind tunnel lift coefficients for all planforms are plotted in Figure 10. The elliptical planform peaks with the highest lift coefficient followed by the tapered planform. However, it can be seen that the tubercle planform does not stall in the range tested. Its slope decreases, but the lift coefficient continues to rise while all the others fall off after stall. At high angles of attack it has the highest lift coefficient. The previously mentioned paper determined that the addition of tubercles on an idealized humpback whale flipper (using a NACA 0020) delays the stall angle by approximately 40% while increasing lift and decreasing drag. We can see similar results for the lift with the NACA 0015. Figure 12 shows the comparison between the wind tunnel lift coefficients for the rectangular and tubercle planforms.

The wind tunnel drag coefficients for all planforms are plotted in Figure 11. The results for drag are less distinct with the curves crossing back and forth over each other and all having fairly similar values. The drag force is smaller and therefore harder to measure and the wall effect in the wind tunnel test section is not always easy to predict.
The remaining figures in this paper were generated using COSMOS FloWorks. Figures 13 and 14 show the pressure distributions on the rectangular and tubercle planforms. It can be seen that the blue low pressure region on top of the wing extends farther back on the tubercle planform.

![Figure 13. Pressure Dist. on Rectangular Planform](image1)

![Figure 14. Pressure Dist. on Tubercle Planform](image2)

Figures 15 and 16 show the velocity distributions on the rectangular and tubercle planforms. It can be seen that the red high velocity region on top of the wing extends farther back on the tubercle planform.

![Figure 15. Velocity Dist. on Rectangular Planform](image3)

![Figure 16. Velocity Dist. on Tubercle Planform](image4)

In Figure 17 the dark blue areas indicate low pressure in between the tubercles. This causes the flow to be redirected in between the tubercles as can be seen in the trajectory plots in Figures 20 – 26. Figures 18 and 19 show how cut plots can be used to look at the pressure or velocity.
distributions on any slice of the wing. In Figures 27 and 28 the rectangular planform is in a stalled condition and the flow separation can be seen.
Figure 23. Flow Trajectories at 13 degrees with Tubercles

Figure 24. Flow Trajectories at 13 degrees Rectangular Planform

Figure 25. Flow Trajectories at 20 degrees with Tubercles

Figure 26. Flow Trajectories at 20 degrees Rectangular Planform

Figure 27. Rectangular Wing in Stall at 15° Angle of Attack

Figure 28. Rectangular Wing in Stall at 20° Angle of Attack
VI. Conclusions

The vision statement for CDIO states, “The CDIO Initiative offers an education stressing engineering fundamentals, set in the context of the Conceiving-Designing-Implementing-Operating process, which engineers use to create systems and products.” The CDIO approach is to integrate and weave CDIO experiences throughout the curriculum.

The skills involved in the design process (solid modeling, analysis, simulation, CAD/CAM, rapid prototyping, testing, systems integration, documentation, and team work) should be learned, developed, and practiced throughout the undergraduate experience.

The exercise of these skills whenever possible in theoretical engineering courses will not only improve the practical abilities of students, but can also improve theoretical understanding and retention.

Bibliography