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Aerodynamics Airfoil Project: Analytical, Numerical, and Experimental Introduction for Undergraduates

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Abstract: In an upper-level, undergraduate, elective fundamental Aerodynamics engineering course, engaging students, and ensuring the learning is impactful is supported through an eight-week project that incorporates analytical, numerical, and experimental analysis of an airfoil. This project allows students to apply what they have learned in lectures, including thin-airfoil theory, dimensional analysis, and wind tunnel operations. This undergraduate research project, a "high-impact practice," introduces the students to the variety of research methods in a way that typically cannot be accomplished in one class with a specific focus outside of research methods. Basic airfoil analysis allows for a simplified approach to undergraduate research. The project results show that many students need further exposure and repetition to understand and appreciate research methods, non-dimensional numbers, and comparison techniques. However, all students showed a tremendous interest in approaching this project and were much more knowledgeable about the methods after the project.

The pedagogical theory used is experiential learning theory. Rather than tell the students about the types of research methods available, the students were asked to put those methods into practice as part of the project. Research has shown that this is an effective way to increase retention of knowledge and is one of the recommended approaches to increase inclusion in the classroom by diversifying teaching methods. The work was done individually albeit collaboratively, so that the students could work together answering each other's questions. This project was determined to be easily incorporated into the lecture-style course, at a manageable level for the students while providing students with an introduction to the three research methods of analytical, numerical, and experimental.

Motivation

An existing fundamental aerodynamics course (an upper-level, undergraduate, engineering elective course) was heavily reliant on extensive derivations and advanced engineering mathematics. After over a decade of being offered in this format, it was noted that most students avoided this elective course, particularly students in marginalized categories in STEM (women, Black, Indigenous, and other People of Color (BIPOC)), and a different approach was needed. One step implemented was to incorporate a project into the course that allowed for more experiential learning; other changes included the change-over of instructors and the primary text to *Hidden Figures: The American Dream and the Untold Story of the Black Women Mathematicians Who Helped Win the Space Race* by Margot Lee Shetterly [1], thus grounding the topics of the course in a historical biography. For the project, the level and depth of the experiences needed to be manageable, since the course was focused on the introduction of aerodynamic topics based on an understanding of fluid mechanics. An approach that allowed students to quickly learn and apply the three research methods of analytical, numerical, and experimental, was implemented, while at the same time students developed professional documentation skills via a research paper.

Implementing research into coursework is one of eleven High-Impact Practices (HIPs) as stated by Kuh in 2008 [2] and presented by the American Association of Colleges and Universities [3]. HIPs have been shown to improve academic persistence and success of marginalized students, therefore making them inclusive teaching practices. “The goal is to involve students with actively contested questions, empirical observation, cutting-edge technologies, and the sense of excitement that comes from working to answer important questions,” AAC&U [3]. The pedagogical theory used is experiential learning theory. Rather than tell the students about the types of research methods available, the students were asked to implement those methods as part of the project. Many others have written about the implementation and significance of undergraduate research [4], [5], [6], [7], often for honors students, and of demonstrating the various methodologies of analytical, numerical, and experimental in a control course [8].

An airfoil project in an undergraduate engineering course is not novel. Various publications exist around research-focused courses [9], and directed or independent study projects [10], [11]. Beck presented a similar concept for a course in 2006 [12], where the focus of the course was the project, with the course content developed around the research. Post et al. implemented a design-build-test-fly project in 2010 into a fluid mechanics course that walked students through numerical and experimental methods [13]. In the project presented in this paper, the research is presented at a level that is not the focus of the course, but complimentary to the course, and is updated for what is available at the US Coast Guard Academy in the current decade. This scaled back version is easier to incorporate into an existing lecture class, with a balance of the time and effort to apply the methods, mostly from teaching the students new software. This paper will present how this project was implemented and made approachable without dominating the course footprint. This model for the project could easily be implemented into similar existing courses or used as inspiration that a lecture-based course can implement research.

Implementation

This project was first implemented in the spring 2022 semester and repeated in the spring 2023 semester at US Coast Guard Academy. The first offering had 9 students, who did the project independently. In 2023, there were 22 students, and based on the constraints of the experimental component of the project, namely the 3D printing and use of the wind tunnel, students were grouped into eleven groups of two students each. The students chose their own partners. The work was done individually, but collaboratively, so that the students could work together answering each other’s questions.

The only prerequisite for the course is Fluid Mechanics, required for Civil, Mechanical, and Naval Architecture & Marine Engineering majors, or Ocean Dynamics, a similar course taken by Marine and Environmental Science majors, covering flowrates and the Bernoulli equation. Therefore, in the context of research, any software used would have to be simple enough for a student to accomplish the tasks in a reasonable timeframe (several hours at most).

There were five parts to this project: (1) airfoil selection, (2) analytical analysis, (3) computational analysis, (4) experimental analysis, and (5) final report. Students were provided a grading rubric that outlined what Exemplary, Good, Marginal, Unacceptable, or Missing elements of the final grade were. Since the project was overlayed on the course, students were given about one week each for the airfoil selection and the final report, and two weeks each for each method (analytical, computational, and experimental), for a total of eight weeks, or just over half of the semester. The basic nature of the project could have been completed in two-three weeks if it were the focus of the course but spreading it out allowed for balance with the other elements of the course.

Airfoil Selection

Students were instructed to search for an airfoil that already had published drag and lift coefficients so they would be able to compare their results to something else. This selection took place about six weeks into a fourteen-week semester, after students had already been introduced to airfoil definitions like camber and thickness, as well as NACA 4-digit airfoils. Allowing students to select their own airfoil builds ownership in the project; they are not limited in any way except that there is existing lift and drag data. Students who are interested in helicopters can choose a helicopter rotor airfoil shape, or students interested in wind turbines can choose a wind turbine airfoil shape. Also, since there is an additive manufacturing (3D printed) component for the experimental testing, they will get to keep their airfoil at the end of the semester. They are asked to answer questions that will help them later complete an “introduction” for their final report: (1) What is the airfoil you chose? (2) What is this airfoil used for? (3) Why did you choose it? , and (4) What does this airfoil look like? They also must start a table for drag and lift coefficients for a range of angle of attack. This is then submitted as the first piece of the project. Having students submit their work in pieces forces them to manage their time well and balance due dates with other elements in the course.

Analytical Analysis

Thin-airfoil theory is derived over three lectures in the course, starting with potential flow theory, Kutta-Joukowski Transforms, and then thin-airfoil theory [14]. The integral equations for thin airfoil theory can be developed easily as MATLAB code [15]. To reduce the workload on students, they were provided the MATLAB script by the instructor to calculate lift coefficients for their airfoil. Drag is zero for this inviscid flow theory application. The input for the MATLAB code is the coordinates of the mean camber line, as defined in the theory. Once students input the coordinates of the mean camber line, the lift coefficients from $-10°$ to $+10°$ were provided. This results in a straight line based on the theory. Results are only provided for this range since small angles were assumed in the derivation. As a submittal due two weeks after the airfoil selection, students are asked to provide the following information that, again, will become part of the methods and results section of their final paper: (1) Briefly describe thin-airfoil theory, giving the key equations for the lift coefficient, assumptions, and limitations of the theory, (2) What is the drag?, (3) Provide a summary of the results for the Lift Coefficient and other parameters you find interesting (is it a straight line or curve, do you see stall? Would you see stall?), and (4) Why $-10°$ to $+10°$?. They then augment their existing table for their airfoil with the new lift coefficients for thin-airfoil theory data. Up to this point, they now have existing lift and drag coefficients and the thin-airfoil theory lift coefficients.

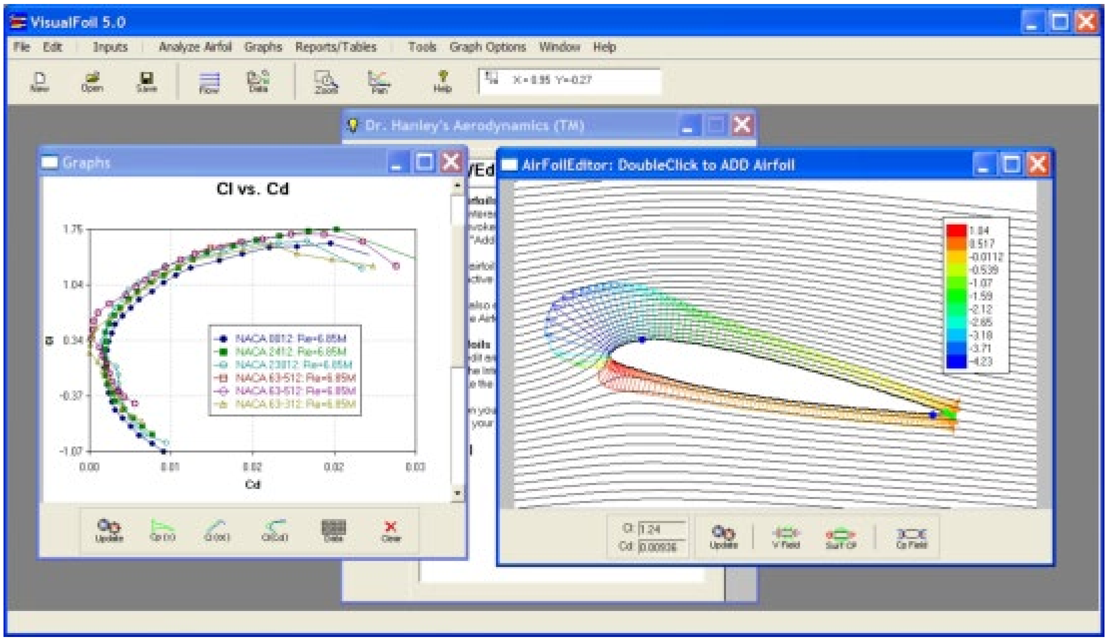

Figure 1: VisualFoil 5.0 software interface for numerical lift and drag coefficients, Hanley Innovations [16].

Numerical Analysis

Numerical analysis is typically the most time-intensive computational method to learn well enough to use for the unique purpose of the research. However, the point of this project is not to learn new software but to do a brief application of computational methods. Fortunately, for airfoils, several software packages exist that are easier to learn. The most accurate while also being the quickest to learn was found to be VisualFoil 5 by Hanley Innovations [16]. VisualFoil 5 uses a linear strength vortex panel method, a boundary layer solver, and stall model. This allows for fast and accurate flow results with the only input from users being the shape of the airfoil, either from a drop-down list of NACA airfoil, or inputting the coordinates of another airfoil shape. A class package of the software was provided to the students for use in the project, and students found the software easy to manage. The submittal for this portion of the project, which students had two weeks to complete, was to (1) Discuss the VisualFoil 5 Software and what the model incorporates, and (2) Compare these results to Thin Airfoil Theory results. Why might they be similar or different? The drag and lift coefficients were easily taken from a table inside the software for students to augment their existing data, now with thin-airfoil theory and numerical results. VisualFoil 5 also offers NACA data as available, which, for those who chose a NACA airfoil, helps them corroborate the data they collected in the Airfoil Selection portion of the project. Figure 1 shows the interface of VisualFoil 5.0.

Experimental Analysis

Based on the majors that include the prerequisite courses for this course, some students taking this course have extensive CAD and 3D printing skills, while others have none. Therefore, the experimental preparation of a 3D printed model needs to still be simple enough for a novice to

Figure 2: Hampden H-6910-12-CDL Wind Tunnel with 5-inch chord-length airfoil loaded at -15° angle of attack. The Wind Tunnel has a pitot-static tube, manometer, and lift/drag load cell. Clockwise from top left: airfoil loaded on the load cell that reads both drag and lift data; the full test section with manometer and pitot-static tube behind the airfoil; full wind tunnel. Flow is left to right.

accomplish in a few hours. The instructor provided a handout for the software most used in their program, Rhinoceros, Version 7 SR9 [18], that provided the novice CAD users with step-by-step instructions to import the coordinates of the airfoil to create a five-inch chord length by five-and-a-half width model of the airfoil with a 0.25-inch hexagonal pocket, 0.1-inches deep to epoxy in a 4-40 nut after 3D printing for easy installation in the wind tunnel, test section sized 8-inches by 8-inches with a square access port of 5 inches each side.

Models were then printed on Ultimaker Cura additive printing machines. Students were trained during a class period in how to conduct experiments with their 3D printed airfoils in a Hampden H-6910-12-CDL Wind Tunnel with Lift and Drag readout. A novel device was developed to vary the angle of attack on the airfoils so students could get lift and drag force data at -15°, 0° and 15° angle of attack. A pitot-static tube connected to a manometer was used to determine the flow speed, linking the subject matter in class to the operation of the wind tunnel. Dimensional analysis requires Mach similarity, which can be accomplished for certain subsonic flows with this wind tunnel (0 to 50 mph), but the models are distorted from the prototypes (not achieving similarity) and therefore students are to take this into account in the discussion. No analysis was done to correct for the distortion as this is beyond the scope of the project. Wind tunnel distortion corrections is too detailed a subject to fit into this broad research experience. Figure two shows the wind tunnel with an airfoil in the test section as an angle of attack of -15°.

The submittal for the experimental analysis asks the following questions to the students: (1) What CAD software did you use? (2) What is the scaling factor (model vs. prototype (reality))? (3) How do Reynolds number and Mach number compare? (3) What velocity should you test your airfoil at in the wind tunnel for Mach similarity? and (4) How many inches of water should the manometer read to get to that velocity?

This submittal occurs before the experiments are run, and afterward the lift and drag coefficient data is added to the table that they have been developing throughout the project.

Final Report

The students completed a formal project report following the formatting of AIAA, the American Institute of Aeronautics and Astronautics. Using a professional society formatting allows students to become more familiar and comfortable with the standard research report. They were provided with a Microsoft Word document template provided to all AIAA authors. Table 1 shows the sections required for the final report. Succinctness and clarity are emphasized. This is not meant to be a large lift, but more so practice in professional, technical communication.

Results

This project was first implemented in the spring 2022 semester, and again in the spring 2023 semester. At the time of this paper, only final feedback of 2022 was available. When asked about the project, three of the nine students responded as shown in Table 2 in an end-of-course survey.

Table 1. Final Report sections required for the Airfoil Project.

Section	Notes
Abstract	Write your Abstract last. Your Abstract is a lot like your conclusion, only it should draw the reader in and want to know how you did all that cool stuff.
Nomenclature	
Introduction	Discuss your airfoil selection here
Methodology	
Analytical Methodology	
Numerical Methodology	
Experimental Methodology	
Results & Discussion	Your ONE figure with all the data and a legend that you got should go here, and you should talk about it
Conclusion	
References	

Table 2: Spring 2022 end-of-course student survey responses about the Airfoil Project.

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
The airfoil project was interesting.	3 (100 %)	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)
The expectations for the airfoil project were reasonable.	2 (66.67 %)	1 (33.33 %)	0 (0 %)	0 (0 %)	0 (0 %)
I understood how the airfoil project related to the course material.	3 (100 %)	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)

Discussion

Students enjoyed getting to select and 3D print their own airfoil. One student wrote, “Learning how all three (Analytical, Numerical, and Experimental) come together was really important for good closure on the course.” Another student wrote, “It was really cool to actually take what we had learned in lecture and make a physical representation of what we had learned.”

Students did request not to have to submit a final report, and in spring of 2022, when a guide for using CAD was not provided, one student requested that it be provided in the future. This was a large part of the impetus to create a step-by-step handout for those who had not learned any CAD in their program of study. In the first offering, the student unfamiliar with CAD had to rely heavily on classmates to help them. Other students wished they could have 3D printed an entire plane, but the complexities of analyzing an airplane are beyond the scope of this fundamental aerodynamics course.

The results of the submitted final reports showed that many students need further exposure and repetition to understand and appreciate research methods, non-dimensional numbers, and comparison techniques. However, all students showed a tremendous interest in approaching this project and were much more knowledgeable about the methods after the project.

Conclusion

By providing students with access to MATLAB [15] code for analytical thin-airfoil theory, VisualFoil 5 software [16] for numerical analysis and CAD, 3D printers, and a Hampden Wind Tunnel, students were able to apply what they had learned in a fundamental aerodynamics class through undergraduate research. This experiential learning project provided students a memorable way to see what they were learning in lecture, while not displacing or requiring extra time or course credits to complete the research. Further repetition of research practices is encouraged, as this brief, single exposure in an elective course is introductory, but a solid foundation has been presented to the students.

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