Implementation of Integrated ThermoFluid Experiments in WPI's Discovery Classroom

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Abstract

An integrated experimental, analytical, and numerical approach to engineering education was developed and implemented in introductory fluid-thermal science courses at Worcester Polytechnic Institute (WPI). Central to the implementation of these innovations is a facility at WPI known as the Discovery Classroom. In this facility the traditional lecture hall has been redefined to combine a multi-media classroom, an adjoining experimental laboratory, and computational facilities to produce an environment where non-traditional learning takes place. We have designated the approach using this facility as the DIANE philosophy: **D**aily **I**ntegration of **A**nalytical, **N**umerical, and **E**xperimental methods into engineering classes. In a typical application, experimental apparatus are demonstrated directly in class during an engineering lecture. Real-time quantitative data are acquired from the apparatus, and the data are analyzed and compared to concurrently developed theory by the students in class. The objective of this approach is to help students better understand relationships between the physical experiments and theory, while gaining an awareness of the integration of various modes of engineering analysis. This approach also allows the effective inclusion of significant experimental components into courses taught within WPI's seven-week term structure. Three introductory undergraduate engineering classes at WPI, fluid mechanics, heat transfer, and aerodynamics, were re-designed. Student assessment of the innovations indicated that approximately 90% of 275 students preferred the re-designed courses to traditional lecture-oriented courses, while also believing that they gained a better understanding of engineering fundamentals.

1.0 Introduction

Over the past few decades, there have been dramatic changes in the way engineering principles are applied to practical problems. Increasingly, an integrated approach using analytical, experimental, and computational approaches is being utilized. The development of compact, powerful digital computers has been one prime mover in these changes, with computational algorithms now often replacing experiments as primary analytical tools. However, experiments still play a crucial role in developing in students an understanding of complex thermofluid phenomena. Additionally, the analytical (exact solution) approach still has an important place in bringing intuitive insight into a problem. For these reasons, engineering programs in academia are increasingly stressing integrated design problems in response to the current engineering practices in industry.

There is some concern that the U.S. educational system is ill prepared to meet the challenges arising from these changes in engineering practice. For example, the overwhelming majority of formal student-faculty contact hours in engineering education remains based on the in-class lecture. The weaknesses of the traditional lecture as the prime source of academic learning, have however become clear.[1-3] Specifically, many feel that the exclusive use of lectures can create a passive learning environment that reinforces any pre-existing “teach me” attitudes in students.[4] Ongoing research in educational methods at WPI[5] has also suggested that traditional lectures can constrain students’ learning,[6] and confirms the need for more interactive components (between faculty and students) in traditional courses. In addition, in formal lecture-based courses, the focus is often largely on the theoretical rather than on concrete examples and/or demonstrations of principles.[7] This points further to an increased need for alternate approaches to traditional lectures.

The National Science Foundation, while addressing areas for education improvement,[8] has specifically encouraged the development of discovery-oriented learning environments and technology-based instruction at all educational levels that capitalize on the full power of new communication, information, and visualization technologies. Since many concepts in fluids and heat transfer are difficult for students to grasp, we felt that an approach that substantially and meaningfully extends simple classroom lecture and textbook work was needed. The implementation of this approach at WPI is the subject of this paper.

1.1 Objectives

The objectives of the innovations reported here were to:

- Bring the excitement of discovery into the engineering classroom by stressing real-time acquisition of data and student 'discovery' of fundamental concepts in non-traditional lectures, thus increasing students’ interest in the thermal/fluid sciences.

- Allow students to understand relationships between physical phenomena and concurrently developed theory through non-traditional lectures and interactive exercises.

- Develop student awareness of the integrated nature of various modes of engineering analysis, the advantages, limitations, and appropriate context for use of each, and their incorporation into the design process through integrated experimental-analytical-computational design exercises.

- Provide the student with hands-on experience in modern experimental, data acquisition, and computational techniques.

2.0 Mechanical Engineering Education at WPI

The innovations considered here were implemented within the Aerospace Engineering Program in the Mechanical Engineering Department at WPI. Aerospace Engineering students receive a specialized degree within Mechanical Engineering that involves a series of six core courses stressing aerospace applications. Four fundamental thermofluid courses in the thermal sciences (Heat Transfer, Introduction to Fluid Mechanics, Introduction to Thermofluid Science, and Classical Thermodynamics) are completed by Aerospace Engineering students prior to their specialized course sequences. In addition, all other Mechanical Engineering students are required to complete three of these fundamental thermofluid courses as part of graduation requirements, resulting in total student populations of approximately 350 students/year in these courses.

At WPI, all undergraduate courses are conducted during a seven-week term in which the typical course meets four or five times per week. Therefore the undergraduate fluids, heat transfer, and aerodynamic courses must cover a large amount of material in a short time. The resulting rapid pace is known to be a common problem in thermofluids and heat transfer courses.[1] In the teaching of heat transfer specifically, students are presented with numerous new concepts and empirical correlations, and spend most of their time learning to apply them correctly to textbook problems.[1] In the process, they may not develop a solid physical understanding of the heat transfer phenomena they are studying, even though the physical concepts are not difficult in most cases. In addition, the large class size in these courses makes scheduling traditional laboratory exercises (which have always provided some degree of active learning[9]) difficult.

2.1 Descriptions of re-designed WPI thermofluids courses

The fundamental thermofluids courses at WPI are Heat Transfer, Introduction to Fluid Mechanics, Introduction to Thermofluid Science, and Classical Thermodynamics. This sequence of courses is taken during the sophomore and junior years. The subsequent Aerospace Engineering Program core sequence consists of the following courses: Aerodynamics I, Supersonic Aerodynamics, Propulsion, Aerospace Systems Design, Astronautics, and Aerospace Structures. This sequence is taken during the junior and senior years. Historically, laboratory requirements in the thermofluid and aerospace areas have been met with a single, dedicated course, Engineering Experimentation, resulting in a lack of connection between theory and experiment. Experimental and computational laboratories have also been conducted on an ad-hoc basis by each faculty member using the limited instructional laboratory apparatus available.

Three introductory thermal-fluid science courses were re-designed incorporating the DIANE Philosophy with the new experimental apparatus. The courses were; 1) ES3004, Introduction to Fluid Mechanics – sophomore level, 2) ES3003, Heat Transfer – sophomore level, 3) ME3711, Aerodynamics I – junior level. Approximately 275 total students in nine sections were enrolled in the re-designed courses. The courses are described below.

Introduction to Fluid Mechanics (ES3004) - A study of the fundamental laws of statics, kinematics and dynamics applied to fluid mechanics. The course includes discussion of fluid properties, conservation of mass, momentum and energy, and hydrostatics as applied to real and ideal (potential) fluids. Laminar and turbulent flows, non-dimensional analysis, dynamic similarity, internal and external viscous flows, and basic boundary layer theory are also addressed. This required, sophomore year course has four sections and approximately 120 total students per year.

Heat Transfer (ES3003) - A course designed to provide an understanding of fundamental concepts of heat transfer, including an understanding of the coupling of fluid mechanics and thermodynamics. Experience in modeling engineering systems and predicting their behavior is also emphasized. Topics covered include steady state, multi-dimensional and transient conduction, natural and forced convection, heat exchanger analysis and design, radiation, boiling, and condensation. This required, sophomore year course has two sections and approximately 200 total students per year.

Aerodynamics I (ME3711) - A first course in the science and engineering of heavier-than-air flight vehicles. Topic include application of fluid mechanics and thermodynamics principles to study lift and drag, the effects of viscosity and compressibility, thin airfoil theory, source/vortex panel methods, aircraft performance and stability. The theory of airfoil circulation is developed and used to examine induced drag, downwash, ground effect and vortex wake turbulence. Longitudinal, lateral, and turning stability of aircraft are considered for both static and dynamics conditions. This required, course has one section per year with approximately 30 students. The course is at the junior/senior level.

3.0 Approaches

3.1 Discovery Classroom

The Discovery Classroom is the centerpiece of the reforms discussed in this paper. The Discovery Classroom, shown in Fig. 1, is a 3500 square foot facility in WPI's Higgins Laboratory. In the Discovery Classroom, the traditional lecture hall has been redefined to include a 90 seat multi-media lecture hall, an adjoining experimental laboratory (800 sq. ft.), and computational facilities which combine to form an integrated learning environment.

This multi-media lecture hall contains a Pentium-based PC at the front of the lecture hall with data acquisition capabilities (LABVIEW software & data acquisition system) which is linked to a projection system with a large video screen. This faculty computer is also linked to existing notebook computers (Digital HiNote VP567) at the student desks (one per two students). The notebook computers (the terms notebook and laptop computer are used interchangeably here), which are department owned and supplied, are loaned out to students for use in the classes. We believe that in the future a majority of students will own notebook computers, and that classroom use of these computers for interactive exercises and exams will become a paradigm. These computational facilities are linked to both campus and global networks.

The multi-media lecture hall of the Discovery Classroom also facilitates the use of experimental apparatus in engineering classes. Services such as compressed air, water, and electric power

(110V/220V-3 phase) are provided at the front of the lecture hall, allowing the experimental apparatus to be incorporated directly into classroom instruction. Direct physical access is provided between the multi-media lecture hall and the adjoining experimental laboratory. The experimental apparatus are set up in the adjoining experimental lab prior to class, and wheeled into a demonstration-teaching area at the front of the lecture hall for use in integrated class exercises during class. A video camera is also provided in the multi-media lecture hall so that the real-time demonstrations can be projected onto the large video screen for better viewing by students. The experimental laboratory contains the same utilities as the multi-media lecture hall, allowing for laboratory sessions by students on the same experimental apparatus outside of class. The in-class demonstrations are one way to help fill the gap between teaching resources and specific learning needs.[9] Experiments are conducted both to illustrate important concepts in the course, and to make the most effective use of one-hour lectures within WPI's compact, seven-week course structure.

3.2 Development of Integrated Classroom Exercises using DIANE Philosophy: Fluid Mechanics and Aerodynamic Courses

The classroom innovations in the fluid mechanics and aerodynamics courses generally consist of an integrated sequence of: 1) non-traditional lectures which utilize the experimental apparatus directly in the lecture hall, 2) interactive classroom exercises in which students compare real-time data from in-class experiments to concurrently developed theory, and 3) interactive classroom exercises in which students compare real-time data to computational simulations on notebook computers. These innovations were incorporated beginning with the 1997-98 academic year. Refinement and further development of this approach has continued over the past three academic years.

The new demonstration apparatus introduced into the fluid mechanics and aerodynamic courses include several hydraulic bench demonstrations, a wind tunnel, and a laminar flow table. The hydraulic bench, consisting of a pump, volumetric flow measurement, and water storage, serves as a multi-purpose flow supply for several experimental apparatus. The hydraulics bench supports standard fluid demonstrations, including a draining water tank flow to introduce mass conservation concepts, a jet impact apparatus showing fluid momentum principles, and a converging-diverging nozzle apparatus to introduce the Bernoulli principle and equation.

The portable wind tunnel is a 12' long mobile Eiffel-type wind tunnel, 8" × 8" × 24" long test section. The maximum flow speed is 110 mph with a turbulence level under 0.25%. The tunnel includes a 5-axis sting balance allowing for lift, drag, and moment measurements, a pressure measure system for measurement of up to 24 pressures on airfoil surfaces, and standard ancillary experiments, such as airfoil and aircraft models, drag models, a boundary layer plate, and wake velocity rakes. Figure 2 shows the portable wind tunnel in use during a lecture in the aerodynamics course.

The laminar flow table demonstrates the principles of potential flow. It enables classic potential flow situations to be studied using laminar water flow between two closely spaced glass sheets (Hele-Shaw flow). Potential flow patterns (streamlines) are visualized using a dye injection system. Combinations of free-stream, and source/sink flows can be visualized, as well as flow over classic aerodynamic bodies (cylinders, internal flows).

3.3 EXCITE Exercises

In a typical classroom exercise, experimental apparatus is extensively incorporated into an engineering lecture. The objective of these interactive exercises is for students to understand relationships between the physical experiments and theory, while gaining an awareness of the integration of the various modes of engineering analysis. In the fluid mechanics and aerodynamics courses, real-time quantitative data are acquired from the apparatus directly in class during experiments conducted by the faculty member (with student volunteer help). The data are immediately analyzed and compared to concurrently developed theory by the students. We have termed these faculty-student interactions as EXCITE (**EX**ample Problems **C**omparing **I**n-class **T**heory and **E**xperiments) exercises. The EXCITE exercise is introduced as an in-class example problem, however in this case all data used in the example problem are obtained from the in-class experiment.

Whenever possible, students use the various flow apparatus to analyze an identical geometry with experimental, computational, and analytical methods to develop insight into the advantages/limitations of each approach. To accomplish this goal, computational simulations (run on the laptop computers at student desks) are also used in the EXCITE exercises. For example, in ME3711 – Introduction to Aerodynamics, flow over a NACA 4412 airfoil is demonstrated in a portable wind tunnel. Lift and drag data are obtained and correlated with thin airfoil theory results and a computational software code based on a vortex panel method. In Figure 3 a typical EXCITE exercise handout used in the aerodynamics class is presented. Here, elliptic finite wing theory is emphasized. An in-class example problem is first analytically solved. Students then collect and process data from the wind tunnel experiment for comparison to the analysis. The lift-curve slope ($dC_L/d\alpha = 3.22 \text{ rad}^{-1} \cong \pi \text{ rad}^{-1}$) for the flat plate airfoil (with wing vortex effects) is shown to: i) dramatically reduce from the classic value for a two-dimensional airfoil ($dC_L/d\alpha = 2\pi \text{ rad}^{-1}$) and ii) match the analytical prediction quite well.

All EXCITE experiments were selected to illustrate fundamental concepts in as simple and clear manner as possible, and to avoid having the experiment resemble a black box.[1] In the fluid mechanics and aerodynamic courses, EXCITE exercises are incorporated into approximately 50% of the course lectures. Specific EXCITE exercises stressing velocity measurement and aerodynamic coefficients, static and stagnation pressures, moments on airfoils, numerical integration of pressure distributions, airfoil lift-curves, finite wing theory, and aircraft stability are incorporated into the Aerodynamics I course. EXCITE exercises stressing unsteady mass conservation (draining tank), momentum principles (jet impact apparatus), velocity measurement, the Bernoulli principle and equation, dimensional analysis and Reynolds scaling, external viscous flow and drag coefficients are incorporated into the Introduction to Fluid Mechanics course.

We believe that the EXCITE exercises allow students to understand relationships between physical phenomena and theory in a far better fashion than is traditionally done in experimental laboratories, which are often run by a teaching assistant with less experience than a faculty member. These real-time experiments are integrated with conventional lectures, as we believe the expository nature of the standard lecture still plays an important educational role (e.g. in conveying mathematical concepts). The comparison of calculated and experimental results during these exercises can lead to a better understanding of the accuracy of correlations, the impact of simplifying assumptions, and experimental accuracy issues.[1] The authors anticipate a future publication in which a more detailed discussion of the pedagogical advantages of the EXCITE exercises is presented.

The EXCITE exercises do not necessarily limit the hands-on experience gained by students on the experimental apparatus and simulations. In the fluid mechanics and aerodynamic courses, 3-4 person lab groups perform traditional laboratory sessions (with teaching assistant guidance) in the adjoining experimental laboratory utilizing the same equipment as in the non-traditional lectures. In these sessions students are asked to extend the EXCITE exercises, for example by studying a wider range of parameters or addressing additional fundamental concepts.

3.4 Heat transfer approaches

In ES3003 - Heat Transfer, a slightly different approach is taken than for the fluid mechanics and aerodynamic courses. For the heat transfer experiments, each apparatus is essentially brought to a steady-state condition before a given lecture. This is dictated essentially by the relatively long time required for heat transfer experiments to reach steady-state compared with the fluid dynamics experiments. The operational features of the experiments are illustrated in class to provide a qualitative demonstration of heat transfer phenomena such as linear conduction, forced convection, and radiant heating. The students are subsequently presented with detailed data for several operating configurations and test conditions for each heat transfer experiment. These data are acquired prior to the lecture by the instructor and/or teaching assistant over a period of several hours. A handout is developed for each experiment to provide supporting technical information, thus helping to free the student to participate fully in the activity without taking notes.[9]

When allowed by experimental limitations, actual data are taken in the classroom by a student volunteer who monitors the experiment during the lecture period. This is best suited to the demonstration of unsteady heat transfer phenomena, such as the cool-down of a pre-heated cylinder by convective cooling in a cross-flow. In all cases the students, in groups of 3-5, prepare a brief, summary report describing the problem, the experimental conditions, and their analysis of the heat transfer data.

The heat transfer experiments available for incorporation into ES3003 include a conduction apparatus, a cross-flow heat exchanger, a radiation demonstrator, a tube-in-tube heat exchanger, and a pool boiling apparatus. The conduction heat transfer apparatus allows demonstration of thermal conduction in both one-dimensional and axisymmetric geometries. Different test specimens, each instrumented with thermisters for temperature measurement and insulated from the surroundings by Teflon insulation, are installed between the apparatus heating elements and water cooled sections to allow the determination of conduction heat transfer rates. For the 1-D case, specimens are provided with both constant and non-constant cross sections, and consist of different materials, including composite materials designed to illustrate contact resistance effects.

In the cross-flow heat exchanger, air flows over electrically heated tubes, either by a blower for forced convection, or without a blower by natural convection. The entire 24” length of the 7.5” by 9.5” working section is visible owing to a transparent front plate, allowing unimpeded visual access to the heat transfer elements and the surrounding flow. Either a single cylinder or a cylinder array can be mounted in the working section. Other heat transfer geometries, in particular, those developed as part of the heat transfer Design Project discussed in the following section, can be readily fabricated and installed into the heat exchanger apparatus.

With the thermal radiation demonstrator, radiant energy emitted from various sources, including a filament element and flat plates, is absorbed by media with different absorption characteristics. The metal flat plates have wide range of emissivities. Both plane and cylindrical radiators, each with near black-body characteristics, are also provided. The unit is equipped with thermocouple probes for surface temperature measurement, a photoelectric cell, and a multijunction thermal detector/radiometer.

The tube-in-tube heat exchanger apparatus consists of concentric copper tubes ½” and 1” in diameter. The heat exchanger can be configured, by opening and closing valves, to run in either a parallel flow or counter-flow heat exchanger configuration. In addition, the outer tubes can be used to examine cross-flow free-convection from a heated cylinder. Water flow velocities of up to 4 ft/s can be run in the heat exchanger to allow students to observe the marked change in heat transfer characteristics that accompanies the transition from laminar to fully turbulent pipe flow. The pool boiling apparatus shows heat transfer by convection boiling, nucleate boiling, transition boiling, and film boiling. The clear 4” diameter Pyrex boiler tube allows students a clear view of the boiling process. The tube-in-tube heat exchanger and the pool boiling apparatus have not been used in the heat transfer course to date.

3.5 Heat Transfer Design Project

As part of the integration of experimental apparatus and analysis into the heat transfer course, students are assigned an open-ended Design Project. The students are asked to design a cross flow heat exchanger consisting of individual cylindrical elements. While the size of the individual elements and the maximum overall array dimensions, are determined by the existing hardware, the students are free to select the number of heat exchanger elements (up to a maximum of 27), as well as their arrangement and all inter-element dimensions. They are also required to analytically predict both the heat transfer performance and the associated pressure loss for their array designs for specified element temperatures and air flow rates. Students carry out the Design Project in small groups, each consisting of 3-5 students (the same individual groups formed to digest the in-class experiments). Of the several designs submitted, the most promising design, based on the instructor’s assessment of the design rationale and the reasonableness of the predicted results, is selected for testing. The selected design configuration is then fabricated in the Mechanical Engineering machine shop and the actual heat transfer performance tested in the cross flow heat exchanger apparatus. The results of that testing, and the comparison between predicted and actual heat exchanger array performance, are then reported to the entire class and discussed.

3.6 Practical Concerns

In this section we address certain practical concerns and ‘lessons learned’ during the implementation of the DIANE Philosophy. The intent is that this discussion would aid faculty at other schools in implementing our approach. First, we should point out that a major renovation of the primary Mechanical Engineering building at WPI, Higgins Laboratory, was undertaken around 1995. This enabled development and construction of the Discovery Classroom in Higgins Laboratory. The development of the multi-media classroom and adjoining experimental laboratory obviously plays a large role in the successful implementation of our approach. However, we feel that the approach could also be applied in a department with fixed physical classrooms and laboratories. Portable experimental apparatus could easily be moved from an experimental laboratory to a classroom, even if the laboratory and classroom are separated by a larger distance, provided adequate physical facilities and access (elevators, ramps, etc.) exist. An initial concern in our approach was the required set-up time for the portable experimental apparatus in the classroom. We have found that with proper planning (i.e., ‘dress rehearsal’ of EXCITE exercises in the laboratory prior to class) the logistics of moving and setting up the apparatus are manageable. In fact, even for our largest and most complex apparatus (wind tunnel experiments), set-up times on the order of five minutes are achievable. This allows for set-up within the ten minutes between classes typically scheduled.

4.0 Student Assessment

The general response to the introduction of the DIANE Philosophy and EXCITE exercises into the classroom was strongly positive, as seen from the results presented in Table I. The overwhelming majority of the students responding to the survey felt that the in-class experiments, and the associated data analysis and reporting, helped improve their understanding of fundamentals in the thermal and aerospace sciences. Interestingly, although the introduction of the in-class and laboratory experiments requires extra effort on the part of the student, 90% of the survey respondents stated that they would, given a choice, prefer to take a course with the added experiments than a more traditional, lecture-only type of course.

The students were also asked their views on conducting the experiments in the lecture hall during class in ES3003. Roughly 2/3 of those responding stated that they would prefer to keep the experiments in class, combined with the lectures. Reasons commonly cited for this included the convenience associated with not having to schedule a separate lab period (in ES3003) and the time savings (heat transfer experiments, for example, take a relatively long time to reach steady-state conditions). In the words of one student, “you can accomplish a lab and lecture in one day,” a significant plus given WPI’s short seven-week term structure. Those in favor of the in-class experiments generally said they were satisfied with the ability to see clearly the experiments, both directly and via the video projection system.

The minority of students who would have preferred to have the experiments conducted in the adjoining experimental laboratory in ES3003 pointed out the benefits of understanding the experiment better by actually doing it (more “hands on”). The chance to take more time with the experiment (both to allow greater familiarity with the experiment and to allow the instructor more time to explain both the equipment and the underlying principles) was also suggested as a possible improvement. As discussed earlier, ‘follow-up’ lab exercises were conducted in ME3711 and ES3004 to address some of these concerns.

The surveys in 1998 and 1999 for ES3003 – Heat Transfer included questions about the Heat Transfer Design Project. Of those responding, 85% stated that they found the Design Project, which involved the design and performance estimation of a cross-flow heat exchanger array, either “somewhat useful” or “very useful” in developing their understanding of heat transfer. Part of the reason for the popularity of the Design Project may be that students often take an added interest in a problem if they know that their solutions will be subject to a physical test.[1] One factor behind the negative responses (15%) may be the preference of some students for specific answers, rather than open-ended problems.[1] Some of the respondents suggested that the Design Project could be improved by increasing its scope, so that the Project would be equivalent to an exam grade (1/4 of the overall grade). Others felt that more background and concepts relevant to the specific design problem would be appropriate.

5.0 Summary & Conclusions

An integrated experimental, analytical, and numerical approach to engineering education has been developed and implemented in introductory fluid-thermal science courses at Worcester Polytechnic Institute. To support these innovations, a unique facility known as the Discovery Classroom has been developed. This facility combines a multi-media classroom with an adjoining experimental laboratory. Integrated classroom activities (EXCITE exercises) were implemented in which real-time data from experimental apparatus are compared to concurrently developed theory and computational simulations. The objective of this approach is to help students better understand relationships between the physical experiments and theory, while gaining an awareness of the integration of various modes of engineering analysis. Student assessment of the innovations indicated that approximately 90% of 275 students preferred the re-designed courses to traditional lecture-oriented courses, while also believing that they gained a better understanding of engineering fundamentals.

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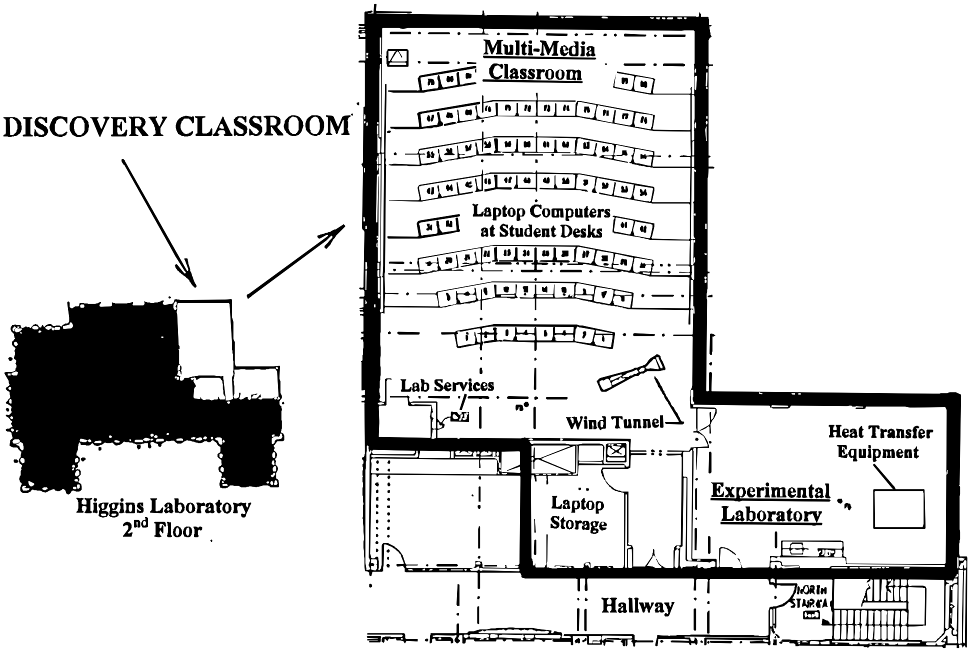
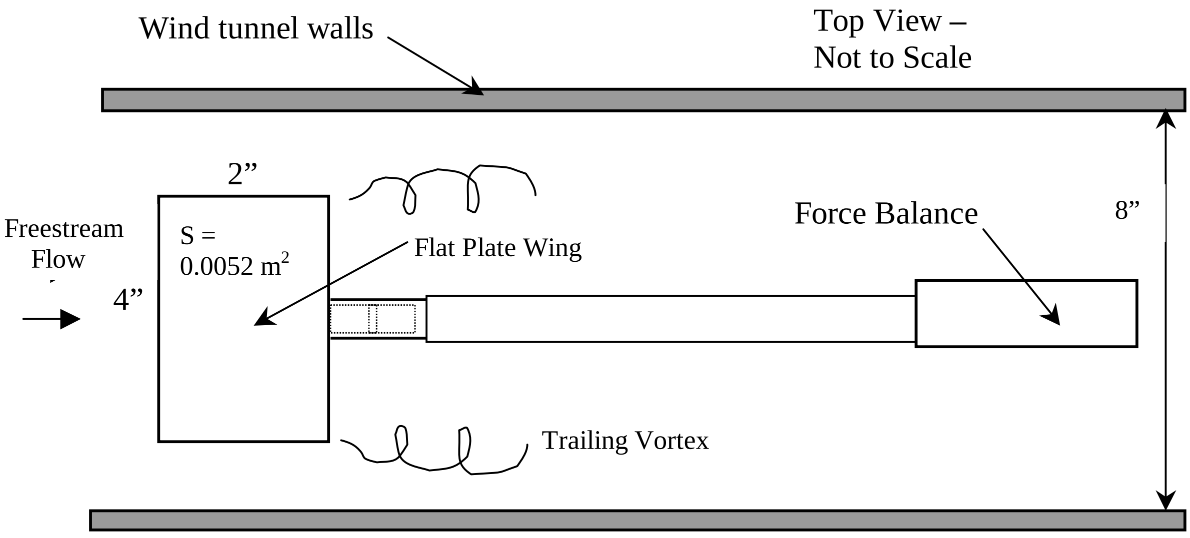


Figure 1: Floor plan of the Discovery Classroom located in Higgins Laboratories at WPI.

Figure 2: Portable wind tunnel and laptop computers in use in Aerodynamics class in Discovery Classroom at WPI. The wind tunnel is positioned in the same approximate position as in the schematic of Figure 1. The entrance to the adjoining Experimental Laboratory can be seen behind the entrance section of the wind tunnel in this photo.

EXCITE #6
FINITE WING THEORY



Example Problem

A thin flat plate wing is placed in our classroom wind tunnel. The wind tunnel freestream velocity is set to its maximum value of 50 m/s. The airfoil has a 4 inch span and a 2” chord. The airfoil is attached to a strain-gage based force balance that can measure the normal force on the airfoil. Use the elliptic wing theory developed in class to approximate the wing and find the following.

Analysis **Completed in class**

a) Wing aspect ratio

$$AR = \frac{b}{c} = \frac{b^2}{S} = \frac{(2/39.3)^2}{0.0052} = 2.0$$

b) Lift curve slope $a = \frac{dC_L}{d\alpha}$ for the wing.

$$a = \frac{a_o}{1 + \frac{a_o}{\pi AR}} = \frac{2\pi}{1 + \frac{2\pi}{2\pi}} = \pi \ rad^{-1}$$

c) Lift coefficient for wing at angle of attack of 8 degrees.

$$C_L = a(\alpha - \alpha_{L=0}) = \pi(8-0)\frac{2\pi}{360} = 0.44$$

d) Induced angle of attack $\alpha_i = \frac{C_L}{\pi\, AR} = \frac{0.44}{2\pi} = 0.07\, rad = 4.0 \deg.$

e) Induced drag coefficient $C_{D,ind} = \frac{C_L^2}{\pi AR} = \frac{(0.44)^2}{2\pi} = 0.031$

Experiment

Data collected during class lecture.

α^o	N (lb)
8	***0.82***
0.	***0.02***

$$C_L = C_N \cos\alpha = \frac{N \cos\alpha}{q_\infty S} = \frac{\boldsymbol{0.82} \cos \boldsymbol{8}}{1500\ (0.0052\ )} x\, 4.44 \frac{N}{lb} = \boldsymbol{0.46}$$

$$C_L = C_N \cos\alpha = \frac{N \cos\alpha}{q_\infty S} = \frac{\boldsymbol{0.02} \cos \boldsymbol{0}}{1500\ (0.0052\ )} x\, 4.44 \frac{N}{lb} = \boldsymbol{0.01}$$

Comparison between analysis and experiment made in-class for parts b) and c) above.

$$\frac{dC_L}{d\alpha} = \frac{\boldsymbol{0.46} - \boldsymbol{0.01}}{8 \deg\ .} x \frac{360 \deg}{2\pi\ rad} = \boldsymbol{3.22}\ rad^{-1}\ !!$$

$$\pi \cong 3.14\ rad^{-1}$$

Graphical techniques used to emphasize differences between 2-D airfoil curves and 3-D wing curves in-class.

Plot lift coefficient vs. angle of attack using Microsoft EXCEL.

Figure 3: A typical EXCITE exercise handout used in the Aerodynamics class. Elliptic finite wing theory is emphasized. An in-class example problem is analytically solved, after which wind tunnel data is collected, processed, and compared to the analysis predictions. All bold-italic numerical entries are completed by students in class.

Table I. Summary of Course Effectiveness Survey Results

<table>
<tr><th>Course</th><th colspan="6">Heat Transfer
(ES3003)</th><th colspan="6">Aerodynamics I
(ME 3711)</th><th colspan="6">Intro. To Fluid Mechanics
(ES3004)</th></tr>
<tr><td>Statement</td><td colspan="3">SA+A</td><td colspan="3">D+SD</td><td colspan="3">SA+A</td><td colspan="3">D+SD</td><td colspan="3">SA+A</td><td colspan="3">D+SD</td></tr>
<tr><td>The in-class experiments helped me better understand the material in this course</td><td colspan="3">80%
N = 97</td><td colspan="3">20%
N = 24</td><td colspan="3">96%
N = 68</td><td colspan="3">4%
N = 3</td><td colspan="3">86%
N = 74</td><td colspan="3">14%
N = 12</td></tr>
<tr><td>I felt that comparing experimental data from the experiments with analysis was beneficial</td><td colspan="3">87%
N = 102</td><td colspan="3">13%
N = 19</td><td colspan="3">NA</td><td colspan="3">NA</td><td colspan="3">93%
N = 80</td><td colspan="3">7%
N = 6</td></tr>
<tr><td>Given a choice, I would rather take this course, rather than a “traditional” course (e.g., solely ‘lecture based,’ with no experiments)?</td><td colspan="3">90%
N = 103</td><td colspan="3">10%
N = 18</td><td colspan="3">98%
N = 66</td><td colspan="3">2%
N = 1</td><td colspan="3">91%
N = 78</td><td colspan="3">9%
N = 8</td></tr>
<tr><td>Given a choice between having less homework and more experimental lab-work, more homework and fewer labs, or no change, I prefer:</td><td colspan="2">ML
18%
N = 24</td><td colspan="2">LL
10%
N = 19</td><td colspan="2">NC
66%
N = 73</td><td colspan="2">ML
23%
N = 11</td><td colspan="2">LL
8%
N = 4</td><td colspan="2">NC
69%
N = 33</td><td colspan="2">ML
37%
N = 30</td><td colspan="2">LL
10%
N = 8</td><td colspan="2">NC
53%
N = 44</td></tr>
</table>

Explanations: “SA+A” is the percentage of respondents stating they either agreed or strongly agreed with the statement; “D+SD” is the percentage that either disagreed or strongly disagreed. “ML” means more experiment lab-work, less homework, “LL” means less lab-work, more homework, and “NC” means no change. “NA” indicates that the question was not included in the survey for a specific course.