Chapter 1

Educating the Future: Impact of Pedagogical Reform in Aerodynamics

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1.1 Introduction

In recent years, engineering curriculum reform has received serious attention from industry, government, and academic groups as the need for change in engineering education has become a well-recognized problem. Within aerodynamics, the need for re-engineering the traditional curriculum is critical. Aerodynamics has been revolutionized by the development and maturation of computational methods. At the same time, educational research in the sciences has demonstrated that learning can be significantly improved using pedagogical methods that differ from the standard lecture approach. These factors cast significant doubt that the traditional aerodynamics curriculum and pedagogy remain the most effective education for the next generation of aerospace engineers.

This paper describes a five-year effort to reform the undergraduate aerodynamics education at the Massachusetts Institute of Tecnology. The decision to pursue educational reform in aerodynamics was stimulated not only by the external forces mentioned above but also by personal experiences teaching the subject. In particular, we had found that our students had limited abilities to

deal with aerodynamic problems that were different than the specific situations covered in the course. For example, the semester prior to modifying our curriculum, a final exam was developed to assess the students ability (1) to apply concepts to different situations than encountered during the semester, and (2) to integrate concepts and apply them in a more complex, open-ended problem, i.e. the type of problems they would face as practicing engineers. The student performance on the exam was very poor and neither ability was demonstrated. Although we thought our students were achieving a deep level of conceptual understanding through our teaching, they were not. As a result, in the final exam, we assessed skills that the students did not have a good opportunity to develop through the subject's pedagogy. Since we felt strongly that conceptual understanding and an ability to integrate concepts to solve complex problems was a primary goal in our subject, we resolved to change our teaching.

The reform of the curriculum largely focused on three issues, specifically:

1. The application of active learning to enhance conceptual understanding.
2. The integration of theoretical, experimental, and computational techniques into a modern aerodynamics curriculum.
3. The use of a semester-long aerodynamic design project to provide educational motivation and authentic learning experiences.

The initial two years of this work was described by Darmofal *et al.*[3]. This paper describes the current pedagogy which has been refined since that initial report and, more importantly, includes a variety of data demonstrating the improvements resulting from the new pedagogy.

1.2 Course Overview

Aerodynamics (M.I.T. subject number 16.100) is one of a set of upperclass subjects that undergraduates have the option of using to complete their degree requirements. The course is offered once a year in the fall semester and during the past five years the enrollment has been approximately 40 students. Prior to this course, students have some exposure to basic fluid dynamics including conservation principles, potential flows, and some incompressible aerodynamics including thin airfoil theory and lifting line.

The main objective of this subject is that students acquire the ability to formulate and apply appropriate aerodynamic models to estimate the forces on realistic three-dimensional configurations. The major topics covered are: 2-D/3-D potential flows (incompressible to supersonic) including panel and vortex lattice methods; boundary layer theory including the effects of transition and turbulence; shock waves and expansions fans; 2-D/3-D Euler and Navier-Stokes computations including some basic turbulence modeling; and, wind tunnel testing.

1.3 Conceptual Understanding and Active Learning

Within cognitive science, the constructivist model of learning has become popular as it explains a large body of experimental evidence on learning and problem-solving[13, 11]. The constructivist model of learning argues that individuals actively construct their knowledge through testing concepts on prior experience, applying these concepts to new situations, and integrating the concepts into prior knowledge. A difficult situation arises when new (presumably correct) concepts conflict with existing (presumably incorrect) concepts. Unless the learner has been given strong reasons to reject these misconceptions, these new concepts will be difficult to accommodate and learning is generally superficial and short-term.

In the area of physics education, Halloun and Hestenes investigated the impact of initial knowledge on student performance in a first course in physics[8]. To do this, they developed a diagnostic test to assess a student's knowledge of Newtonian concepts. The diagnostic was carefully designed to include misconceptions that students frequently possess from personal, everyday experience with motion. The results showed that initial knowledge (as assessed by a pre-test using the diagnostic) was the dominant indicator of performance in the physics courses while factors such as the specific instructor, academic major, high school mathematics, gender, and age had no impact. Furthermore, the post-test performance on the diagnostic showed that the overall performance on the exam, while better than in the pre-test, was quite poor. Thus, while students could perform well on the usual course exams that determined their grades, the conventional instruction they received did little to alter their misconceptions about mechanics.

The importance of pre-existing knowledge and the constructivist model of learning casts considerable doubt on traditional instruction. Traditional teaching uses a transmittal approach in which students are assumed to gain knowledge while passively listening to lectures giving rise to the analogy between students and blank slates. This style of teaching is in direct conflict with a constructivist view of learning as it does not account for the need for students to actively confront their misconceptions such that they may be replaced by a more advanced understanding. Thus, simply improving the quality of the presentation of concepts within a lecture will not result in a greater understanding, rather, the constructivist model of learning suggests that a more substantial change in pedagogy is required to address misconceptions.

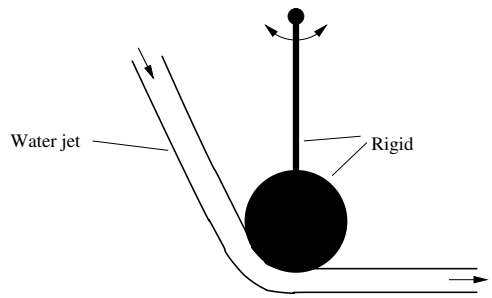
One strategy for strengthening conceptual learning is a set of pedagogical methods known as active learning. Bonwell & Eison define active learning as instructional strategies that involve "students in doing things and thinking about the things they are doing"[1]. By this definition, a traditional lecture in which students passively listen to presented material is not an active learning

strategy. Rather, active learning requires some type of student engagement of the material during class. Utilizing the physics exams developed by Halloun and Hestenes, Hake showed that active learning methods had a statistically-significant improvement on learning gains compared to traditional lecturing in a study of six-thousand students from a wide variety of college (and some high school) campuses[6]. Furthermore, educational research shows that this active learning can also increase confidence, enjoyment of a subject, and inter-personal skills[12].

During the Fall 1999 semester, we began using peer instruction, an active learning approach developed in physics by Mazur[9, 2]. In this approach, conceptual questions (referred to as ConcepTests by Mazur) are given to students in class with time for individual reflection. After a check to see how well students have understood a question, small group discussions may be held. In addition, the instructor will usually clarify misconceptions and lead students in further exploration of the concept often giving a mini-lecture. In a typical class, two-to-three concept questions are usually discussed. Several options exist for measuring the class understanding. In 16.100, we have found the use of a handheld personal remote to be very effective. The personal remotes have several advantages over hand-raising or flash cards including anonymity of student responses and the efficient generation of assessment data to analyze aggregate performance. The use of peer instruction in a set of sophomore aerospace engineering courses is also discussed by Hall *et al.*[7]

To illustrate a typical concept question, consider the generation of lift. The generation of lift on an airfoil is filled with many misconceptions due to the (usually inaccurate) folklore regarding how airplanes fly and further complicated by the knowledge gained in previous courses. In discussing lift generation, a series of concept questions are used concentrating on understanding lift generation through momentum changes, streamline curvature, and reaction forces. The first question involves the impingement of a water jet on a cylinder as shown in Figure 1.1. Although many students believe the jet will cause the cylinder to be propelled away from the stream, in actuality, the object will rotate into the stream. A simple momentum balance leads directly to the connection between force (lift) generation and momentum change. When we use this question, we include an in-class demonstration that clearly demonstrates the cylinder being drawn into the stream. This question is then followed by a series of questions connecting the concept of flow turning to force generation, and extending the ideas to understand the loss of lift at stall when the airfoil no longer turns the flow as effectively.

Our experience with concept questions has shown that the students must have some experience with the material prior to class. Otherwise, discussing concepts and misconceptions is nearly impossible since students are not likely to have encountered much of the material prior to the course. To address this, reading assignments and graded homework are given that are due prior to dis-



A jet of water impinges a cylinder attached to a pendulum. Which way will the pendulum swing?

1. Into the water (clockwise)
2. Away from the water (counter-clockwise)
3. Not enough information

Figure 1.1: Concept question example

cussing the material in class. The use of pre-class homework is a significant shift from traditional engineering pedagogy in which homework is assigned and due only after discussing the material in class. Not only is the pre-class homework critical to the success of active learning in the classroom but it also encourages student self-learning. Furthermore, by scanning the homework assignments, student misconceptions and common difficulties can be detected immediately rather than only week(s) after discussing material. With the improved student preparation, the classroom becomes a significantly more active environment with increased faculty-to-student and student-to-student discussions on the subject's concepts.

In addition to changing our in-class pedagogy, we have also modified our exams from a written to an oral format. While written exams can only analyze the information that appears on paper, i.e. the final outputs of a student's thought process, an oral exam is an active assessment which can provide greater insight into how students understand and relate concepts. Also, oral exams are adaptive to each student. If a student is stuck or has misunderstood a question, the faculty can help the individual. As opposed to a wasted assessment opportunity, the dynamic adaptivity of an oral exam raises the likelihood of an effective assessment. Finally, practicing engineers are faced daily with the real-time need to apply rational arguments based on fundamental principles. By using oral exams, this ability can be directly assessed.

1.4 Integration of Theory, Computation, and Experiment

Our past aerodynamics curriculum had a significant focus on theoretical aerodynamics with some limited exposure to experimental and computational aerodynamics. However, as suggested by Murman & Rizzi[10], "today's aerodynamics engineer needs to be fluent in modern CFD methods and tools, and must know how to utilize them in conjunction with theory and experiment for aerodynamic analysis and design." The difficulty is how best to integrate computational methods into the mainstream aerospace curriculum.

We envision that the large majority of aerospace engineers will only have experience with the results of a CFD calculation, some engineers will be end-users of CFD, and a very small fraction will be involved in some aspect of CFD development. Thus, our general philosophy for integration of computational aerodynamics into our undergraduate course is that the underlying aerodynamic approximations embodied by a computational tool must be well understood by a modern aerodynamicist, however, the details of the numerical methods are less important. For example, we expect students to understand that a three-dimensional, compressible Euler calculation can model shock waves but, being inviscid, is not appropriate when viscous effects might be critical. By contrast, we do not expect students to understand what a second-difference artificial dissipation operator is, or how flux-difference splitting differs from flux-vector splitting.

Computational and experimental methods are integrated in the course through the use of a design project (described in more detail in Section 1.5). The project requires that the student teams develop validated aerodynamic models for the required operating conditions. To do this, students perform both computational simulations and wind tunnel tests. Furthermore, since the student teams are required to reduce and correct the raw wind tunnel data, they begin to appreciate how wind tunnel testing is as much of a model as purely theoretical or computational techniques. In the process, students quickly learn that neither computational methods nor experiments are capable of providing reliable predictions for all applications, and understanding both the agreement or lack thereof between simulations and experiment is a crucial role for an aerodynamicist.

1.5 Project-based Learning

Typically, aerodynamics and other advanced engineering topics are taught with a significant focus on theory but little opportunity to apply theory especially to problems that approach the complexity faced in the design of modern aircraft. As a result, students perceive they are learning material 'just-in-case' they may need it later in their careers. In the project-based approach used in 16.100,

the knowledge is immediately being applied. Another advantage of including a project-based approach is that it increases the richness of the pedagogical techniques in the course. This variety of learning experiences has been recognized as a key principle of effective teaching[4, 5].

Over the past five years, two design projects have been developed: one based on a military fighter aircraft and another on a blended-wing body commercial transport aircraft. Both of these projects have an initial modeling phase in which student teams develop and validate aerodynamic models for a baseline configuration, followed by a design phase in which the models are used to improve the aerodynamic performance.

A key feature of our design project implementation is weekly project work sessions. The goal of these project sessions is to provide a scheduled block of time in which the course staff (typically one faculty member and a teaching assistant) can interact with the teams as they begin to tackle the project. These two-hour sessions are held in a large electronic classroom with approximately 25 computers or roughly one computer for every two students. We have found that this ratio of computers-to-students is effective in promoting collaboration. At the beginning of the semester, these project sessions are often used to provide information to the students about the project, clarify requirements, and introduce the various computational tools and experimental facilities. However, later in the semester, the role of the staff tends more towards coaching and trouble-shooting.

The student teams consist of approximately four students. Each team submits an interim and a final written report that is the basis for their grades. For the interim report, which is due roughly 2/3's through the semester, the teams are required to fully describe all of the aerodynamic models they have developed including their validation studies. The final report focuses on using these validated models for design (in addition to correcting any errors found in the interim report). A best-practice that we have found for the design phase of the project is to require the teams to make a hypothesis on what design changes are likely to improve their ability to meet the design requirements based on their conceptual understanding of aerodynamic performance, prior to performing any re-designs. Then, the final design phase becomes a study of whether the proposed design modifications have the desired effects; if not, the students are required to explain why their initial hypothesis was incorrect.

1.5.1 Military Aircraft Design Project

During the summer of 1999, we contacted several industry and government representatives requesting a design project that could serve as the semester-long theme of our aerodynamics course later that fall. Lockheed Martin Aeronautics Company (LMAC) proposed a project based on a typical re-design scenario encountered in the military aircraft industry. Specifically, the student teams

were to develop aerodynamic models of an F-16-like wing-body geometry at several critical operating conditions and then use these aerodynamic models in a wing design trade study. The project was used for three semesters, Fall 1999, 2000, and 2001.

This project includes flight regimes from low subsonic to supersonic speeds including some at high angles of attack. The performance metrics of interest were:

1. The take-off distance at sea level conditions assuming the angle of attack is limited to a maximum of 25 degrees to avoid the tail striking the ground.
2. Radius of action (i.e. range) for Mach 0.9 cruise at 10K ft
3. Dash time estimate from Mach 0.9 to Mach 1.2 at 10K ft

For the subsonic (i.e. take-off) regime, a 1/9th scale wind tunnel model was built and tested in the low-speed tunnel at M.I.T. At high speeds, experimental data was available from previous LMAC tests. The design phase of project focused on improving the take-off, cruise, and dash performance through introduction of leading and trailing-edge flaps, and variations in wing sweep and span.

1.5.2 Blended-Wing Body Design Project

For the Fall 2002 semester, a new design project was developed in collaboration with The Boeing Company based on the Boeing Blended-Wing Body aircraft design. The goal of this project was to redesign the baseline configuration to improve the static stability while minimizing drag and maintaining balance. Specifically, two flights conditions were considered: transonic cruise and low-speed approach. In approach, leading and trailing edge devices were permitted to be active, while in cruise, the aircraft was required to be clean. As in the fighter aircraft project, low speed wind tunnel tests were performed to provide validation data for the aerodynamic models.

1.6 Results

Quantifying the impact of pedagogical change on learning is difficult. Our approach is to take data from a variety of sources and draw our conclusions from the aggregate. While any single source is suspect, taken together, the results are more conclusive.

1.6.1 Effectiveness of Pedagogy

During the past three years (Fall 2001-2003), the pedagogy as described above has remained nearly the same with only minor adjustments. The student ratings

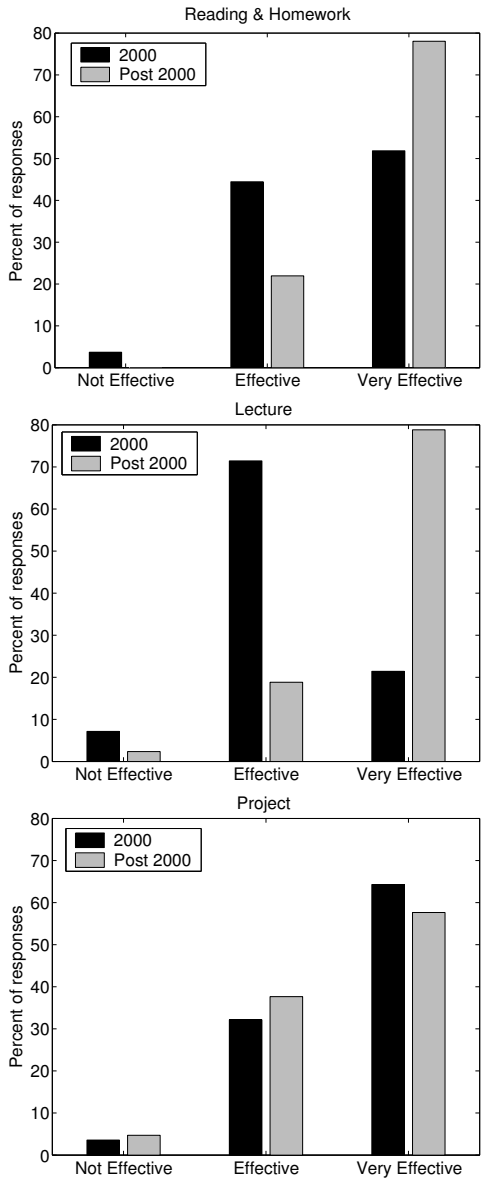


Figure 1.2: Comparison of student evaluations from 2000 and post-2000 (2001-2003) semesters for reading/homework, lecture, and project effectiveness

of the effectiveness of the pedagogy (specifically, reading/homework, lecture, and project) are shown in Figure 1.2. For the post-2000 semesters, the majority of students rated all aspects of the pedagogy as very effective, though the project effectiveness is rated somewhat less highly than either the reading/homework and lecture (this observation on project effectiveness is also consistent with the student comments discussed in Section 1.6.3).

1.6.2 Impact of Pre-Class Homework

The use of challenging pre-class homeworks was found to significantly increase the effectiveness of the lectures. In the Fall 2000 semester, while the pedagogy was as described above, the pre-class homeworks were designed to encourage reading but did not require significant engagement of the material. As a result, the students were not sufficiently prepared for in-class active learning. In fact, the student feedback from the Fall 2000 semester led directly to the decision to increase the homework difficulty. The result of the increased homework difficulty is that the students found not only the reading/homework but also the lecture to be more effective. For example, as shown in Figure 1.2, the percent of students rating the reading/homework and lecture as very effective shows a statistically-significant increase from the 2000 to the post-2000 semesters.

The use of challenging pre-class homework assignments also had a favorable effect on the student exam performance. During the Fall 2000 and 2003 semesters, a written final exam was given. Both final exams consisted of five questions of which three were identical. The remaining two questions were different but of similar difficulty. The three identical questions assessed different skills, specifically conceptual, synthesis, and quantitative abilities. The student performance on these three questions is shown in Figure 1.3.

- **Conceptual Question**: This question focused on the prediction of lift and drag using different types of flow models (e.g. 2-D potential flow, 3-D potential flow, 3-D Euler, and 3-D Navier-Stokes). Students were given different drag polars and lift curves and asked to identify the model that was used to generate each. As can be seen in Figure 1.3, the performance on this question was nearly the same in both years.

- **Synthesis Question**: This question focused on modeling the aerodynamic forces on a refueling boom of a tanker, and required not only recognition of the important physical effects but also some ability to quantitatively model these effects. While the percentage of top scores is similar, the percentage of lowest score (i.e. 0-60%) improved from around 40% to less than 20% from 2000 to 2003.

- **Quantitative Question**: This question focused on the use of an integral boundary layer method to estimate boundary layer growth in a duct flow. The difference in these results shows a substantial improvement from 2000

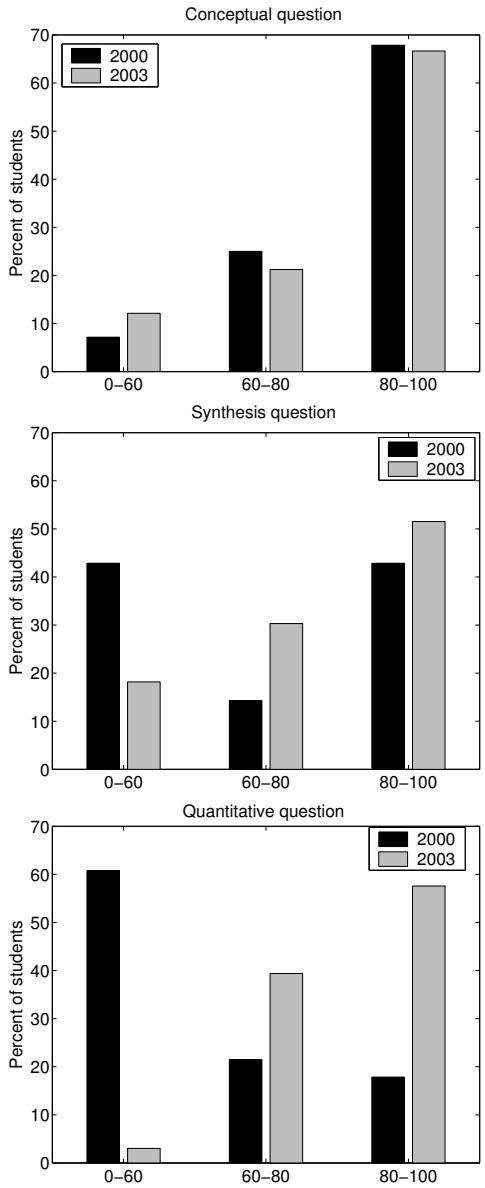


Figure 1.3: Comparison of exam performance from 2000 and 2003 for questions assessing conceptual, synthesis, and quantitative skills.

to 2003. This improvement is not surprising, however, since in 2000 the students had a less opportunity to perform this type of more detailed, quantitative analysis.

Thus, by effectively combining homework (or similar application activities) with concept-based active learning, students can achieve high-levels of performance in skills ranging from quantitative application to synthesis of multiple concepts.

1.6.3 Student Comments

In addition to the effectiveness ratings of the pedagogy, students were given open response questions that asked 'What were the best parts of the course?' as well as 'How could the course be improved?' In this section, we present some of these comments and summarize the main conclusions.

The open-response questions show that students are often initially hesitant about pre-class homework, but by the end of the semester they recognize the benefits of this technique. Some of the comments include:

- *Doing homework before the lectures is good... makes actual learning in lectures possible.*
- *Prof. Darmofal forces you to learn the subject material by assigning homework that he has not covered in lecture, therefore I have to force myself to read the text and go to office hours. When he does go over in lecture after the Pset is due, I did absorb the material much better.*
- *The teaching methods are outstanding... making us read before the p-set is good form.*
- *I was initially opposed to the idea that I had to do reading & homework before we ever covered the subjects. Once I transitioned I realized that it made learning so much easier!!*
- *I was skeptical at first of new techniques like [concept question], homework on material that hasn't been learned in lecture. In the end, it worked out very well. This has been a course where I really felt like I got my money's worth.*

These comments also reinforce the impact of pre-class homework on the effectiveness of the lectures.

Another common theme in the open-response questions is the student satisfaction with the oral exams. Many students find the oral exam to be a more accurate representation of their understanding than more traditional written exams. In fact, several students have said that the oral exams were the best parts of the course. Of the 21 comments made about oral exams in the open response evaluations, 19 were favorable, only one was negative, and one suggested a modified implementation. Some typical comments are:

- *The oral exam was a different learning assessment approach that I liked a lot.*
- *The oral exams are an excellent measure of understanding.*

- *Oral exams [are the best part of the subject], I think these gave a good opportunity to show what you understand.*
- *I really like the idea of the oral final. Even though it is scary, it really shows how much you know about the subject, better than any exam would.*

One of the most challenging aspects of the new pedagogy has been the implementation of the team project. In the first place, the project has multiple facets (in particular the wind tunnel experiments and the computational simulations) that must be successfully managed. Furthermore, keeping ten or more teams of four students functioning effectively can be highly time-consuming for both the faculty and the students. The open-response questions for the past three years clearly show both the benefits as well as the difficulties of the team project. During this time, 31 positive comments were made about the project with only 2 negative comments; however, 29 students suggested the need to improve the implementation. Typical comments include:

- *In a project, you have to take what you learn and directly apply to something. This is more effective than a problem set because it is on a larger scale - while on a problem set you may only perform a calculation once, a project makes you do that many more times. You begin to understand why and when what you are doing is applicable on a much deeper, intimate level.*
- *I think the team projects are really good. There are some kinks which need to be worked out and possibly explained sooner, but they really bring us to an understanding of what elements are necessary to incorporate theory into design.*
- *The projects were very interesting. Learning how to use computational tools and seeing how all the theory and testing is used in conjunction to gain accurate results was very useful and enjoyable.*
- *My group floundered for a while with the project. In the end we got everything to come together, but it was tough to get through. I'm not sure that I would have wanted it any other way, now that I look back on it. I learn best when I struggle with material for a while, provided I have enough time to finally understand it. I had just enough time for the project.*

The students have perceived the educational benefits of applying the material they are learning in class on a complex problem; furthermore, several students (including other comments not shown here) note that the project allowed them to better appreciate how theory and computation compliment experiments in aerodynamic design. However, the effective use of projects remains a challenging issue to address.

1.7 Outlook

In response to external and internal forces of reform, we have re-engineered our undergraduate aerodynamics curriculum. The key ingredients of the reformed pedagogy include:

- active learning combined with pre-class homework to increase conceptual understanding,
- oral exams to assess onceptual understanding,
- a semester-long team project stressing the roles of experiment, theory, and computation in modern aerodynamic design.

The results as measured by student evaluation and performance demonstrate that improvements in pedagogical effectiveness and learning have been achieved. Furthermore, the critical role of adequate student preparation on the effectiveness of active learning was demonstrated. While students often expressed an initial hesistancy with respect to the less-traditional aspects of the pedagogy, they eventually found the methods to be highly effective.

1.8 Acknowledgements

This work over the past five years has involved significant interactions both internal and external to MIT. The initial re-design of the curriculum began as a collaboration with Prof. Earll Murman. The military aircraft project was developed with Lockheed Martin by Mike Love and Dennis Finley. The Blended Wing Body was developed with Bob Liebeck (a Boeing employee and a Professor of the Practice at MIT). During the Fall 2000 semester, 16.100 was co-taught with Professor Steve Ruffin who was on sabbatical from Georgia Tech. This work was partially supported by the National Science Foundation, the MIT Alumni Fund for Educational Innovation, and the MIT MacVicar's Faculty Fellow program.

Bibliography

[1] Bonwell, C.C. & Eison, J.A. *Active Learning: Creating Excitement in the Classroom.* ASHE-ERIC Higher Education Reports, No. 1, 1991.

[2] Crouch, C.H. & Mazur, E. *Peer Instruction: Ten Years of Experience and Results.* American Journal of Physics, **69**, 2001.

[3] Darmofal, D.L., Murman, E.M., & Love, M. Re-engineering Aerodynamics Education, *AIAA Paper 2001-0870*, January 2001.

[4] Felder, R.M. & Silverman, L.K. *Learning and Teaching Styles in Engineering Education.* Engeering Education, 78(7), 1988.

[5] Felder, R.M., *Matters of Style.* ASEE Prism, 6(4), 1996.

[6] Hake, R. R. *Interactive-engagement vs. traditional methods: A six-thousand-student survey of mechanics test data for introducing physics courses.* American Journal of Physics, **66**, 1998.

[7] Hall, S.R., Waitz, I.A., Brodeur, D.R., Soderholm, D.H. and Nasr, R. *Adoption of active learning in a lecture-based engineering class.* 32nd ASEE/IEEE Frontiers in Education Conference, Boston, MA, 2002.

[8] Halloun, I.A. & Hestenes, D. *The initial knowledge state of college physics students.* American Journal of Physics, **53**, 1985.

[9] Mazur, E. *Peer instruction: A Users Manual.* Upper Saddle River, NJ: Prentice Hall, 1997.

[10] Murman, E.M. & Rizzi, A. Integration of CFD into Aerodynamics Education. *Frontiers of Computational Fluid Dynamics - 2000.* Editors: D.A. Caughey and M.M. Hafez. 2000.

[11] National Research Council. *How People Learn: Brain, Mind, Experience, and School.* National Academy Press, Washington, D.C. 2000.

[12] Prince, M. *Does Active Learning Work? A Review of the Research.* Journal of Engineering Education, **93**, 2004.

[13] Wankat, P.C. & Oreovicz, F.S. *Teaching Engineering*. New York, McGraw-Hill. Available at http://www.asee.org/publications/teaching.cfm. 1993.