

# Integrated Teaching Model in Graduate Aerospace Classes: A Trial With Compressible Flow Aerodynamics

#### Dr. Sidaard Gunasekaran, University of Dayton

Sid is an Assistant Professor at the Mechanical and Aerospace Department at the University of Dayton. He got his MS and Ph.D. at the University of Dayton as well. During his doctoral studies, Sid developed a knack for teaching using modern pedagogical practices in mechanical and aerospace classes and engaged in diverse research in Low Reynolds number flows. Sid is an active participant in the Dayton/Cincinnati American Institute of Aeronautics and Astronautics (AIAA) section.

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Sidaard Gunasekaran University of Dayton

## Abstract

Most of the graduate aerospace classes are dominated by complex analysis and a plethora of equations. As such, without proper context, it is very easy for a student to lose sight of the big picture, which hinders them from critically thinking about the knowledge they gained and its applicability in the real world. The recent surge of the modern pedagogical practices at the University of Dayton such as student-centered learning, active learning, co-teaching, problem/project based learning, entrepreneurial mindset learning, flipped classroom, etc., are largely focused on undergraduate classes but not in graduate classes comparatively. This paper documents a teaching model where the homework, projects, activities, lectures and independent studies are all integrated on a single platform (portfolio) in an endeavor to motivate graduate students to practice sustainable learning (long-term learning) and promote critical thinking skills. The author implemented this model for the first time in a graduate compressible flow aerodynamics class with the "portfolio" as a platform of integration. The paper also discusses the application of this model in the compressible flow class with examples, students' reflections and feedback. Students found this model to be different and more effective than traditional graduate classes and were able to connect, apply, understand and appreciate the relationship between the complex mathematical equations and the real-life applications. It was also found that creating a portfolio takes more time and effort when compared to traditional exam based class and the workload might need to be reduced.

# **I. Introduction**

Preparing graduate students to be successful in all aspects of their career has remained a velleity for many years in academia. Recent study finds that the perceptions of the students in their competence in the workforce does not align with the perceptions of their employers. The surge of the modern pedagogical practices in academia such as student-centered learning, active learning, co-teaching, problem/project based learning, entrepreneurial mindset learning, flipped classroom, etc., have helped current millennials to maneuver within the workforce but the gap between the academic preparation and employers' expectations still remains at large [1]. This may be because the majority of the graduate engineering curriculum trains students to perform straight forward analysis with complex equations and does not provide enough emphasis on other skills that are needed and expected from graduate students in the workforce. Being a part of KEEN (Kern Entrepreneurial Engineering Network), most of the modern pedagogical practices at the University of Dayton are largely focused on undergraduate classes when compared to graduate curriculum. KEEN faculty fellows program offers incentives to teachers to develop or modify existing undergraduate classes to incorporate problem based learning (PBL) and entrepreneurially minded

learning (EML). As such, efforts are undertaken to expose undergraduate students to the actual skillset and mindset they need to be successful in their career and not just possess the technical ability to solve a well-posed and well-framed problem. Whereas in a graduate class, on an average, there is very little change in the way the classes are taught when compared to undergraduate classes. At the highest level of the educational ladder, the general assumption seems to be that things will just take care of themselves and scholarship on how to teach graduate students is still thin on the ground <sup>[2]</sup>.

The underlying rationale for any kind of formal instruction is the assumption that knowledge, skills and attitudes learned in a classroom setting will be recalled accurately, and will be used in some other context at some time in the future. Most often teaching and assessment is done as if the underlying rationale for education were to improve students' performance in school. National Institute of Literacy has created a set of literacy standards called "*Equipped for the Future* (*EFF*) Content Standards: What Adults Need to Know and Be Able to Do in the 21<sup>st</sup> Century" <sup>[3]</sup>. Based on the skillset shown in Figure 1, in academia, engineering graduates are trained only to "Use math to solve problems and communicate" while very little effort is made to increase all other skillset shown in Figure 1.



Figure 1 Literacy standards set by National Institute of Literacy [3]

Carnevale and Porro<sup>[4]</sup> elegantly stated that "School-based abilities are not necessarily the same as work-based abilities. Employers want employees with solid academic basics, but they want the applied versions of the three R's. Applied reading, writing, and math are substantially different from the versions taught in schools. In addition, employers want a set of behavior skills that are

not taught at all in traditional academic curricula, such as problem solving, communication skills, interpersonal skills, and leadership." It is pretty straightforward to see that academia has a long way to go in truly *preparing* the students for their career and any type of workforce.

# **II. Elements of the EFF Standard Incorporated into the New Teaching Model**

All of the elements shown in Figure 1 are equally important. However, in a graduate class, it might not be plausible to incorporate all of these elements mentioned in Figure 1 without compromising the technical rigor that is usually associated with the graduate course. The expectations behind the technical rigor of a graduate class might be the reason why students-centered learning has not, for the most part, reached graduate schools yet. And for the same reason, most graduate curriculum tries to squeeze too much information into a brief time <sup>[2]</sup>. By doing so, graduate students lose the ability to retain and apply the knowledge they learned in the class. When it comes to long-term retention and transfer, it has been shown that less is more <sup>[5]</sup>. But as a teacher of any graduate classes, it is always hard to find the right balance between the amount of material to cover and the amount of time spent on a certain topic to ensure thorough understanding.

Therefore, in this paper, only five key elements are incorporated in the new teaching model which can foster long-term learning, decision-making and communication skills without compromising the technical rigor of the course. Each element is described with an example and students' reflections from AEE 553 Compressible Flow Aerodynamics class in which these elements were implemented. The sections refer to the homework problems and handouts given to the class as well. These are attached in the appendix of this paper.

## 1. Application of Concepts and Equations:

Possessing a large volume of formal knowledge is necessary but it is not sufficient to make an original contribution. It is highly imperative to train graduate students to assess the practical applicability of assignments and the concepts they learn in each class. Halpern and Hakel <sup>[5]</sup> suggested that the single most important variable in promoting long-term retention and transfer is practice at retrieval of concepts through various applications. Some of the mathematical concepts become more tangible and relatable for the students if certain applications are attached to it. After all, the class is a part of the engineering curriculum, so it is only prudent to expose the students not just to the equations but also to the real life applications.

## **Example:**

More often principles such as conservation of mass, momentum and energy are taught from a pure mathematical perspective and very little insight is given to students based on their real world applicability. When the author asked a question in the compressible aerodynamics class, "How is conversation of momentum applicable for engine design?", there was no response to the question and when asked what is the equation of thrust, only few students were able to retrieve it from their memory. On an average, it was obvious that the students were not trained to think about conservation laws from a design or an application standpoint. Even if they think they know the concept, they struggle to communicate in an effective way. Using conservation of momentum (assuming no body force, no friction force), the equation of thrust can be determined as

$$T = \dot{m}V_{exit} - \dot{m}V_{inlet} - (P_{inlet} - P_{exit})A \tag{1}$$

where  $\dot{m}$  is the mass flow rate,  $V_{exit}$  is the velocity at the exit,  $V_{inlet}$  is the velocity at the inlet of the engine,  $P_{exit}$  and  $P_{inlet}$  represents the exit and inlet pressure of air and A is the nozzle exit area. In terms of design, it is obvious to see that the terms  $\dot{m}V_{inlet}$  and  $(P_{inlet} - P_{exit})A$  are reducing the thrust generated by  $(\dot{m}V_{exit})$ . This is the reason why all engines have diffusers or inlets to reduce the contribution of  $\dot{m}V_{inlet}$  (also called as RAM drag) to the total thrust. The difference in ambient and exit pressure gives rise to pressure drag which can be reduced by proper design of the nozzle. Therefore, by thinking about the thrust equation from a design standpoint, it allows the students to get a big picture context as to why diffusers and nozzles, the topics they will study in detail in the class, are important in an engine. Setting this context, or allowing the students to think about the big picture is crucial to their understanding of the subject.

#### **Application of Concepts in AEE 553 Compressible Flow Aerodynamics:**

By approaching each equation in the graduate compressible flow class from an application standpoint, it made students appreciate the significance of what it is that they are learning and why. Homework problems were also designed in order for the students to apply the concepts they learned in class to real-world applications. The homework assignments given to the students are attached in the <u>Appendix</u> of the paper. From an application standpoint, students solved homework assignments on:

- F-35 lifting fan (Calculating thrust and lift using conservation of momentum) (HW 1 Q.4)
- F-16 stagnation and static ports (Applying normal shock relations to determine the speed of aircraft and material selection for Pitot tubes) (HW 4)
- F-16 1D inlet and F-15 2D inlet (Determining the efficiency and pressure recovery of each inlet based on true flight data) (In-class exercise)
- F-104 diamond wing (Determining lift on F-104 Starfighter using shock relations) (HW 6)
- Nozzle of NASA's Space Shuttle Main Engine (Determining optimum altitude and optimum area ratio at each altitude of the nozzle) (HW 7 Q2)
- NASA's turbine-less ducted fan (Incorporated to determine the importance of Rayleigh flow) (Rayleigh flow guided notes). As a tangent to the present topic, in an equationcentered course such as compressible flow, guided notes prevent students from the mere copying of equations and derivations from the board and allows them to derive the theories by themselves through proper guidance. In the compressible flow class, students worked in groups to go through the derivation and fill in the missing steps.

"The most incredible part of this class for me was starting with basic conservation equations and slowly building upon them until we found relationships which explain why real-life airplanes, rockets, or wind tunnels are designed the way they are. This really ties it all together for me. Solving things on paper is one thing, but seeing why and understanding is why we become engineers. This class was extremely beneficial to me in that regard and I hope that this portfolio will help me to retain that knowledge well into the future." As observed in the homework assignments, most of the key concepts in compressible flow were approached using airplanes as an application. This had profound impact on understanding of the subject by the students as seen in some of their reflections.

## 2. Open-ended Discussions and Problems:

Modern workplace requires innovation, creativity and the ability to look at a task and not only see the outcome but also different ways to achieve it. Many of the real-life problems are open ended with multitude of variability. Therefore, graduate students should be able to solve open-ended problems by making the right assumptions rather than having the ability to solve back of the chapter straight forward "plug and chug" type problems. Becker and Shimada <sup>[6]</sup>, open ended problems must provide students with "experience in finding something new in the process". Open ended problems should be included in classroom discussions and assignments so that students not only get the opportunity to apply the equations but also discover something new during the process.

## **Example:**

Using the same thrust equation (Equation 1) as an example, an open-ended discussion on the different ways to increase thrust from an engine, will make the students discover that there are only few ways to do it which are increasing exit velocity of the engine, reducing intake velocity, proper design of nozzle where the ambient and exit pressure are the same, and increasing the mass flow rate. The discussion can further continue on this topic making the students think about all the variables that affect the nozzle design and the mass flow rate such as the area ratio, total pressure, total temperature, etc. Throughout this process, students dive down into the minor details of each term in the thrust equation while still having the big picture in mind.

# **Open-ended problems in AEE 553 Compressible Flow Aerodynamics:**

Many open-ended questions were posed in the class and in the homework assignments in the graduate compressible flow class such as

- Role of compressible flow in airplane design (HW 1 Q1)
- Validity of Bernoulli's equation in compressible flow (HW 1 Q2)
- Importance of Energy Equation in compressible flow (HW 1 Q3)
- Use of conservation laws to predict emergency warning systems in a hypothetical situation (HW 2)
- Selection of airfoils for the new Boeing aircraft which satisfies Middle of the Market (MOM) niche (HW 3)

It was discovered that open-ended problems took a long time for the students to solve and there was some intransigence from students' to solve such problems. Their feedback was heard and the author started discussing some of the open-ended homework problems in class without giving too much information for them to solve the problem. Once exposed to the problem in the classroom setting, students inquired what to solve for and were then able to find a path to solve the problem. This type of classroom setting turned the table when compared to the usual homework assignments. In this method, the students were the ones to ask the right question to solve the problem and not the instructor.

"The course was set up in a pretty good manner for a first time in Compressible Flow. Lectures were thoroughly thought out to maximize the impact for students. The healthy mix of learning the derivations, functional relationships, applications, and approaching the open-ended homework provided for effective learning and not being repetitive day in and day out." - Robert S

## **3. Critical Thinking:**

Critical thinking doesn't always confine to solving an equation to get to an answer. While that can be a part of the process, critical thinking often happens through making connections, thinking outside the box, discussions and critiques. The instructors should act as a facilitator to allow for discussion and encourage a freer thought process. More often, critical thinking does not always end with one right answer but with more questions and differing evaluations of the topic <sup>[7]</sup>. Critical thinking allows students to better understand the subject which fosters long term memory. Critical thinking can be incorporated into regular lectures by starting with a question. In most of the classes, the author always begins with questions or group discussions related to the concepts that will be discussed in class. The author also employs critical thinking in the end of the class or after discussing a concept by asking questions such as "Why is this important?" and "Why do we care about learning this in the first place?" and "Where is it applied?".

### **Example:**

Continuing the example of the thrust equation (Equation 1), it is straight forward to use the equation of thrust to calculate thrust using input values. However, by employing critical thinking, students can determine the variables that can affect the thrust produced by the engine as shown in Figure 2. By employing critical thinking and questioning the equation, students can not only determine the multifunctional dependence of thrust but also quantify the sensitivity of thrust due to changes in each variable.



Figure 2 Functional dependence of multitude variables on thrust from engine. Critical thinking is required to understand the sensitivity in thrust due to changes in each variables.

## Critical thinking in AEE 553 Compressible Flow Aerodynamics:

Critical thinking in compressible flow was employed in the classroom, homework assignments and the portfolio which will be discussed in the next section. In the homework problems, students critically thought about

- The limits of Mach number variation behind the shock when compared to the Mach number upstream (HW 5 Q2)
- Relating hydraulic jump and shock waves (In-class discussions)
- Finding the variation of pressure, Mach number for UD-Low Speed Wind Tunnel contraction (HW 7 Q1)
- Differences between types of airspeed (Mini-Project 1 Part 1)
- Effect of compressibility corrections on airplane design (Mini-Project 1 Part 2)

It was enthralling to see students discover by themselves that if not for compressibility corrections, the final design of an airplane would be 30-40% larger than necessary. Teaching them this would not have been effective as them finding this through critical thinking.

"Before solving this problem (Mini-project Part 2), it was not evident to me how important the compressibility flow correction equations are. By taking a step further to critically think about the impact of the solution to the problem, I was surprised to see that without compressibility correction, airplanes would be 40% larger than necessary which increases cost/fuel consumption, etc." - Robert S

## 4. Independent Research:

Golde and Dore <sup>[8]</sup> found that 35% of third-year graduate students did not believe that their graduate coursework laid a good foundation for doing independent research. Independent research is the process of learning through experience and learning through reflection. It is a part of experiential learning where chosen topics are supported by reflection, critical analysis and synthesis. Independent study is structured to require the student to take initiative, make decisions and be accountable for the results. In independent study, the instructors should refrain from providing students with all of the content and information but give them required guidance so that they don't deviate from the topic. Graduate classes should always include independent studies as a part of the pedagogical practices.

## **Example:**

Continuing the example of thrust equation, no matter what type of nozzles engines use, each nozzle has just one design condition where the exit pressure equals the ambient/back pressure. This impacts the design of rocket nozzles because there is only one altitude in which the nozzle produces optimum thrust. As a part of the independent study, students can determine ways to make the nozzle function at optimum thrust condition for more than one altitude. Doing an independent study on this topic will let the students come across variable geometry nozzles, aerospike nozzles, single expansion ramp nozzles, etc which they might not have come across otherwise.

## Independent Studies in AEE 553 Compressible Flow Aerodynamics:

Independent study is an integral part of the portfolio in the compressible flow class and contributes to a significant percentage of the students' score in each portfolio drafts. The content on portfolios will be discussed later in the paper. In each draft, all students are required to do independent studies on at least two different topics related to the content covered in the class every two weeks. This makes the students take personal responsibility in learning and motivates them to learn about the topics that interest them. Occasionally, however, students will be given independent study topics to do in the homework. Topics such as

- Supercritical airfoils (HW 5 Q1)
- Effect of sweep on Aerodynamics (HW 5 Q1)
- Area rule (HW 5 Q1)
- Anti-shock bodies (HW 5 Q1)
- Types of airspeed (Mini-Project 1 Part 1)

were given as independent studies to student as a part of the homework. Students were required to be comprehensive in their answers and were specifically instructed not to provide one sentence answers. Some students really enjoyed the independent study aspect of the course. It provided a source of motivation for them to keep learning about the material.

"As far as writing the Portfolio, I enjoyed it, but the thing I enjoyed most was the Independent studies. I believe this was my main motivation for all the work I put into the class."- Margaret R

"Through independent studies, I got into reading some topics, like the Whitcomb bodies, area rule and Whitcomb as an engineer, Supercritical airfoils, etc and it was refreshing to get on a tangent and learn something new on my own. Thank you for your hard work and determination to push me to accomplish this task." - **Robert S** 

## 5. Technical communication:

None of the above-mentioned elements matter if the students cannot effectively communicate the concepts they learned through their coursework or through their homework assignments to their peers or even to themselves. According to the survey (through interviewing over 140 engineers and taking surveys over 2000 engineering graduates) by the University of Wisconsin-Madison School of Education, most of the engineers commented that only two to three hours were spent in a day looking at the technical details. The majority of their time was focused on interacting with people in marketing, sales, field support and other engineers in different disciplines along with lot of writing, documentation and presentations <sup>[9]</sup>. The survey dictates communication skills were ranked as an essential skill by 62% of the engineers, more than any other skill, and 90% listed it as important on the job. It was obvious from the survey that the conventional didactic approach and mentorship of students in the technical aspects no longer provides a complete education. Students have to be able to communicate what they learned effectively through written, oral or visual communication.

The art of writing essays, summaries and reflection are most often practiced in nonengineering departments such as art, social sciences, business, etc. The majority of the engineering curriculum on the other hand is designed to train students to perform design and analysis and does not provide enough emphasis on communicating a student's learning process. It is scientifically proven that by transforming thoughts into written words, the meta-cognition is increased through formation of new neural networks in the encephalon which results in long-term memory <sup>[10]</sup>. It is also proven that writing can enhance critical thinking and problem-solving skills, as well as serve to identify and confront personal misconceptions <sup>[11]</sup>.

Therefore, in a graduate class, students should be able to communicate their understanding of the subject matter, their method of application of equations, their process of critical thinking and their independent studies through written, oral or visual communication.

#### **Technical Communication in AEE 553 Compressible Flow Aerodynamics:**

#### Written Communication:

Technical communication (written communication) in compressible flow aerodynamics class was achieved through the use of portfolios. However, modules were implemented to incorporate oral and visual communications in the coursework as well. The concept of portfolio is described in more detail in Section IV. In the portfolio, students explain in their own words everything they learn in the class homework assignments, projects, independent studies and classroom discussions. Students also learn to connect the things they learned through different aspects of the class. Doing this forced the students to put their thoughts into words which made them understand the concepts better. However, following a portfolio based learning process involves a lot of challenges which are discussed in Section IV of this paper.

#### **Oral Communication:**

Apart from written communication, oral communication was also fostered in the course. The assessment of <u>HW 3</u> was done through oral communication. HW 3 required students to determine an airfoil that will allow a new Boeing airplane to cruise faster. The students were instructed in the handout to schedule a time with the author for them to present the results in a manner that they prefer. They were required to communicate the process they used to solve the problem and show ONLY the relevant equations that were used. Each student was given 10 minutes to explain the problem and the solution. Students' were assessed by the quality, clarity and the technicality in their oral presentation.

#### **Visual Communication:**

In the final day of the course, students were asked to summarize what they learned in the entire semester in a chart using color pencils and crayons. Initially, the author felt that this exercise would be considered as juvenile for graduate students but after implementation, both the author and the students realized the importance of doing this exercise. By visually summarizing the content students learned in the entire semester, they started to realize how much content they have covered and more importantly, the context they had while discussing the topic. Students related each concept discussed in class to an application. One such visualization is shown in Figure 3.

Even though writing portfolios and creating presentations were lot of work, students quickly realized the impact it had on their day to day life. Two graduate students in the

compressible flow class worked at the Wright Patterson Air Force Base and they dealt with some of the topics discussed in compressible flow such as nozzle design and normal/oblique shock waves. The students reflected that they were able to communicate with the proper lexicon to their peers and superiors at their work force using what they learned in class. The author was surprised to see the impact the emphasis on communication skills had on the students' job performance and even in their research. This is really the point of incorporating this module in the first place!

*"This class was very valuable to me for preparing to write papers and providing technical presentations and providing technical explanations to people I work with."* - Margaret R

"I am currently doing supersonic combustion testing at my lab at WPAFB. This is where I will be applying the knowledge I learned from the compressible flow course. I can't wait to start my thesis research come late-summer, and I strongly believe that compiling this portfolio will be beneficial when it comes to writing my thesis." - Matthew G



Figure 3 Visual communication of summary of concepts discussed in compressible flow class which shows the big picture perspective and connections between each concepts discussed in class.

## **III. Learning Objectives**

Each course should have learning objectives because they provide a direction for the course and set goals for the students and instructors to achieve. The learning objectives of the compressible flow course were conceived such that they could potentially set a direction to the class to achieve the different elements listed in the previous section. The author now uses the following five learning objectives for most of the classes he teaches as they seem to be universally applicable to all engineering classes (especially aerospace classes such as Introduction to Flight, Fundamental Aerodynamics, Turbulence, etc).



Figure 4 Correlation of learning objectives to Bloom's taxonomy. The learning objectives set by the author covers all the different stages of learning.

The learning objectives are:

- **1.** To relate each concept learned in class to the outside world/application (Always having the big picture perspective).
- 2. To explain the fundamental concepts with clarity through written, oral or visual communication.
- **3.** To connect and integrate the different concepts learned through lectures, projects, homework, and independent research.
- 4. To solve open-ended problems by making the right assumptions and performing appropriate analysis using tools learned in class.
- 5. To perform basic experiments and computational simulations related to the coursework.

These five learning objectives are correlated with Bloom's taxonomy <sup>[12]</sup> (Figure 4) to determine if they could help students attain the different stages of learning. This correlation in Figure 4 is based on author's best judgement and perception. Therefore, the correlation is debatable. But from the author's perspective, it is believed that on an average, most of the graduate classes only focus

on the knowledge and analysis stage of Bloom's taxonomy and doesn't provide a platform for students to understand, apply, synthesize and evaluate the concepts they learn in the class.

It is believed that the five learning objectives listed above cover all the stages of learning set forth by Bloom. The author found it worthwhile to share the learning objectives during the first day of the class and it was beneficial to put the objectives in the syllabus with bold letters enclosed by a bang box as shown above. The hope is to let the students know that the author is serious about the learning objectives and everything he does in the class is to achieve those five learning objectives.

These learning objectives made a good segue to introduce the concept of portfolio as well. The portfolio is a platform where students can achieve the stages of learning which are not achieved in other graduate classes. The concept of portfolio and how it was used as a platform of integration is explained in the next section.

# **IV. Platform of Integration – Portfolio**

The teaching model presented in this paper is an endeavor to incorporate all the skillsets mentioned in Section II and the learning objectives mentioned in Section III into the course of AEE 553 Compressible Flow aerodynamics. Most of the graduate classes contain weekly assignments related to the topics covered in class which gave a platform for the students to apply the equations to a given set of problems. These practices are common in any graduate curriculum where homework is the only platform where students have a chance to learn and grow. Exams are usually the way to assess the students' learning ability and understanding of the knowledge.

It was clear from the beginning that homework assignments alone were not going to provide a basis to foster the skillsets and achieve the learning objectives set by the author. A new platform was sought out where the students can integrate all those five skillsets and achieve higher stages of learning. Once such platform used was the portfolio.

## What is a Portfolio?

Cress and McCullough <sup>[13]</sup> elegantly described portfolio as "Diversity and accomplishment announced themselves in exemplary collections designed to overview and promote abilities, strengths and specialties, and signatures that made one different, a cut above the competition". Shackelford <sup>[14]</sup> described student portfolio as "a purposeful collection of materials capable of communicating student interests, abilities, progress and accomplishments in a given area". Christy and Lima <sup>[15]</sup> used student portfolios to initiate student-centered learning. "The portfolio method encourages students to take greater responsibility for their own learning, and makes explicit the life-long nature of engineering education".

In essence, portfolios <sup>[16]</sup>

- Document the progress of students' educational experiences
- Foster active learning and motivate students
- Can be used to share experiences and expertise
- Are instruments for assessment, feedback, and discussion

- Provide students with opportunities for reflection and self-assessment
- Are accessible and easy to upgrade
- Can reflect the conceptual structure of the subject matter

## Why a Portfolio?

It has been known for a while in the academic community that the conventional exam based evaluation method do not assess the true learning of the students <sup>[17]</sup>. Instead, it assesses the students' ability to read and repeat information which is the most rudimentary form of learning. Since each student has different learning abilities and cognitive process (Figure 5), there should be a better way to determine how well the student has learned a subject rather than giving the same exam to a classroom of students with the diverse learning abilities. As Figure 5 clearly portrays, the exam based assessment is not conducive to the students to truly learn the subject.



Figure 5 A new evaluation system must be implemented in academia for individual assessment of each student in classroom because in the words of Albert Einstein – "Everybody is a genius. But if you judge a fish by its ability to climb a tree, it will live its whole life believing that it is stupid". [18]

According to Bloom's taxonomy <sup>[12]</sup>, to facilitate lifelong learning, the evaluation system should require the students to reflect, realize, synthesize, critique and evaluate on the knowledge they learned in the different aspects of the course. Exams doesn't provide enough value for assessing these qualities. This is where the portfolio-based evaluation system proves to be useful. It provides a platform where students can integrate the subject matter they learned from different aspects of the class such as (Figure 6):

- o Lectures
- Homework assignments
- Projects
- Group discussions
- o Independent studies
- Article summaries

Metaphorically, these different aspects of the class are like pieces of puzzles which the students must put together the way they understand the subject and not the way it was taught by the author. As such, the completed puzzle in their portfolio will be unique to each student in the class and will reflect true understanding and knowledge of the student. In the portfolio, students discuss the technical content taught in different classes and the homework assignments and projects are conceived in way that it fits in between the concepts taught between two classes. For example, in Figure 2, the concepts covered in class 1 and class 2 are interlinked by the homework assignment 1. And it is necessary for the students to solve Homework 1 to understand the concepts discussed in the second class.



Figure 6 Integrated portfolio-based model for sustainable (lifelong) learning through reflection, realization, synthesize and critique of knowledge learned from different aspects of class

## **Emphasis on Reflections**

Apart from integrating the concepts from multiple elements of the class, students were required to provide comprehensive reflection on classes, homework assignments, projects, etc. in each draft of the portfolio. Reflection was given a significant priority and weightage which required the students to document their personal view, thoughts, questions, realizations, feelings, etc. in the portfolio. At first, students found it hard to reflect because there was an element of ambiguity in the explanation of the reflections and most students never had the experience of reflecting on the concepts they learned in the class. But upon author's feedback to the students each week, their reflections got better. And no two student's reflections were alike. Requiring the students to reflect on the concepts makes the learning personal and allows the students to take personal responsibility in their learning process. The author could see students' excitement, motivation, frustration, understanding or lack thereof in their reflection which provided an immediate feedback on the style of the class, structure of class, homework and the projects.

#### **Emphasis on Feedback**

The proposed teaching model will never work without consistent and timely feedback from the instructor on students' portfolio. In the compressible flow class, the students were required to turn in portfolio submissions once every two weeks. Students had four classes in two weeks and either one homework assignment or one project which they document in each draft of their portfolio. The author had to grade the portfolios and provide qualitative feedback on the content to make sure students' explanations of concepts through written or visual communication were correct. A sample feedback given by the author in a student portfolio is shown in Figure 7. The author looks for misunderstandings and misinterpretation in students' explanations of the concepts and corrects them. The feedback usually is highly technical and because of that, the grading in this teaching model cannot be left to a teaching assistant. The instructor must take personal responsibility in grading and providing timely feedback because similar effort is expected from the students as well. Based on the instructor's feedback, the students are required to turn in the portfolios for a regrade as well. In the graduate compressible flow class, the author had 10 students. By the end of the semester, each student on an average had around 200 pages in their portfolio. It was soon evident that the grading load for this teaching model was immensely heavy when compared to any other classes. As such, application of this teaching model to larger classes might not be possible. The author is currently working on a variation of the proposed teaching model where the grading workload is manageable for a classroom of 35 students.

What happens when we study the relation between temperature and entropy in Fanno flow? A similar approach was used in Rayleigh flow. We can take equation 162 and rearrange it to isolate the change in temperature is over the change in entropy, as shown in equation 166. Equation 166 has a relation of  $C_{\nu} = R/(\gamma - 1)$  as well to the equation.

$$\frac{dT}{ds} = -\frac{(\gamma - 1)}{R} \frac{M^2}{(1 - M^2)} T = -\frac{M^2}{(1 - M^2)} \frac{T}{C_v}$$
(166)

This relation can be used to plot the effect of Mach number with temperature and entropy. Figure 108 shows this very effect. There are different Fanno lines per temperature and per fluid (changing the T and Cv terms). Not necessarily. As you can see from the graph, the temperature is decreasing with increase in entropy in subsonic case and vice-versa in supersonic case. If the tube length is longer than the characteristic length of the input Mach number, only then the flow will follow a different Fanno line. Otherwise, it will be the same. But if you change the medium, then the Fanno line will change. As you can see from the figure below, flow with friction drives the entropy to increase. With equation 166 though, it approaches a limiting term, or the reference state, which has been discussed before. The reference

Figure 7 A sample feedback from the author in student's portfolio. The red underlined sentences are the author's comments. Focused technical and personal feedback went a long way for the students to truly understand the subject. Feedback in itself became a process of teaching.

#### **Portfolio Evaluation**

In most classes, homework assignments are evaluated on a percentage basis. For example: 70/100. From the author's perspective, this system doesn't provide any helpful feedback to the students for them to improve on the skillsets mentioned in Section II. As such, several criteria for grading portfolio drafts were developed to evaluate the different elements mentioned in Section II.

Each draft of the students' portfolio was evaluated based on

- The level of technical detail in the explanations
- Quantity of technical content covered
- Integration of ideas and concepts from multiple aspects of the class (shown in Figure 1)
- Independent studies on topics related to class discussion
- Inclusion of figures, graphs, and other visual aids to explain a certain concept
- Local and Global Reflection on concepts learned
- Overall impression of professionalism and effort

The weightage for each of these criteria was changed for each portfolio drafts depending on the author's expectations of the students in that week.

This platform of portfolio proved to be great asset to student's learning in the compressible aerodynamics course. Through reflection, realization, critique, synthesis, evaluation and communication of the concepts, students experienced the art of learning in a completely different way. For graduate students who are aspiring to become teachers, the current model gave motivation to practice similar techniques.

"I thought the portfolio method was definitely an effective way of learning for students. It is a way to induce creativity and write about the given subject. This method helped me learn and in a different way and really taught me how I learn. As a Ph.D. student, it helped me find ways to make myself better and think deeper about a subject. All this preparation not only increases my knowledge, but helps me learn about how I write and study, which are important aspects to know, when writing papers or a dissertation, or learning about a specific topic. When I finish my doctorate, I hope to instill a portion of this method in my teaching. Writing this portfolio provided me with insight to the implications of traditional testing methods and how I hope to influence potential students positively to have an impact in society." - **Rob S** 

For this teaching model to be successful, major modification in the teaching style in the classroom was necessary. It was immediately realized that the traditional approach of teaching aerospace classes by writing equations on the board is not going to work. As such, some of the teaching methodologies employed in the present teaching model is discussed in the next section.

# V. Teaching Methodologies

Most of the graduate aerospace engineering classes are based on students copying the numerous equations in their notes, performing weekly/bi-weekly back of a chapter homework assignments from a book, doing one or two projects, taking two mid-term exams and a final exam. This monotonous style of the class makes students vilipend the subject material regardless of its significance. This is one of the reasons why students forget the main concepts and ideas after graduating from the class. In order to promote the skillsets mentioned in Section II and to achieve the learning objectives mentioned in Section III, few elements was incorporated into the teaching methods such as:

## 1. Getting rid of the required course textbook

While having a required textbook can be beneficial, for a subject as broad as compressible flow, it is not fair to have the students confined to just one textbook. In order to foster independent study and critical thinking, students should be allowed to find information from multiple resources through their own efforts. References to several books are mentioned in the syllabus and it was made sure that the referenced books are available in the university library. The alternate intention of not having a required textbook is to break free from the tradition of asking students to solve back of the chapter homework problems. None of the homework problems listed in the appendix of this paper were taken from back of a chapter in a book. Instead, homework questions were designed to be open-ended and real world application oriented as mentioned in Section II. Although it was a lot of work from the chapter HW problems which for the most part doesn't relate the concepts to real world applications.

## 2. Article Summaries

The intention of this module is to give students a few articles from popular aerospace magazines such as Aerospace America, AOPA, Aviation Week, and Unmanned System, to complement the concepts they learn in class. Students were required to write a summary and reflection on the article in their portfolio. This exposes the students to the current developments in the field of aerospace engineering and enlightens the students on how basic concepts they learn in class are applied on a bigger scale. In the compressible flow class only one article summary was incorporated into the portfolio from Aerospace America magazine on sonic booms but multiple article summaries can be incorporated into this teaching model.

## 3. In-Class Group Work/Discussions

In order for this teaching model to be effective, in-class lectures shouldn't just be all about deriving equations on the board and having students copy them. In the compressible flow course, each class begins with the author posing the question, "What did we talk about in the last class?" to summarize the main concepts discussed in the last class which always made a good segue to introduce the new concepts. Practicing this approach made the students participate in discussions in the beginning of the class which creates a positive learning environment. Several in class group discussions were facilitated throughout the semester starting with the first class of the semester. After introducing the syllabus and allowing the students to introduce another student in the class, three questions were posed to the students for a group discussion. Each group consisted of maximum of three students. The three questions are:

- 1. What are the different types of flows?
- 2. What is compressible flow and how you define it?
- 3. What are some of the applications of the compressible flow?

For each of these questions, the students were given 4 to 5 minutes to discuss among their group. The author then called each group individually to convey their answers to the entire class. The author found that this method made the class lively, dynamic and energetic when compared to the

traditional lecture based class. Apart from that, the three questions set an excellent context for the subject of compressible flow and gave them a background to build their knowledge on the subject.

Students also worked on open-ended problems, difficult homework problems and guided notes as a group in class as well. This dynamic learning environment was much appreciated by the students especially given the time of the day at which the class was offered (5 PM to 6:15 PM).

"Lectures were thoroughly thought out to maximize the impact for students. The healthy mix of learning the derivations, functional relationships, applications, and approaching the open-ended homework provided for effective learning and not being repetitive day in and day out. I also liked that it was more conversational during class rather than the traditional lecturing. I appreciated the opportunities to work on or in groups during class to approach and solve problems first, as it develops confidence in our ability to do it ourselves for a job in the future."

### 4. Guided class notes

The author found that in an equation based class, guided notes provided a great way to take the boredom out of the derivations which are crucially important. Guided notes are instructorprepared handouts provided to all students in the class with necessary background information and cues with unfilled spaces to write key facts, equations, concepts, assumptions, etc. during the lecture. A guided notes sample is shown in the Appendix for Rayleigh Flow, a concept discussed in the compressible flow class. Some of the important assumptions, derivation steps and equations were intentionally left out form the notes so that the students could discuss in groups and fill in the blanks. Through this method, the students were able to pay complete attention to the class and were able to ask important questions to the author. The guided notes surprisingly provided a faster way to go through the derivations when compared to writing equations on the board. When it comes to writing on the board, the author particularly does not have a good handwriting which leads to misinterpret some of the students to accurately document the derivations as well. This method can be applied even for a larger class. The instructor should walk around the class and make sure that students are working on the guided notes without being distracted.

## 5. Passion Projects

This teaching module was not successfully implemented in the compressible flow class because of the lack of supersonic wind tunnels and laboratory facilities at the University of Dayton to generate compressible flows. But this module is currently being incorporated in the fundamental aerodynamics class taught by the author. The idea of passion projects was inspired from a project based research class for undergraduate students at Massachusetts Institute of Technology. When students think back on their formidable experiences in the university, it won't be the lectures or the classes they take but the opportunity to take ownership over an independent project and pursue a single idea. This experience will cement student's love for learning and the process of discovery. This is the inherent motivation behind designing the passion projects because it promotes independent study and sustainable residential learning. Throughout the semester in the fundamental aerodynamics class, students have the option to choose two different projects of their interest out of 15 projects which they will work on throughout the semester. This way the students will get a chance to teach their peers about what they learned and enhance the quality of conversation and learning in the classroom.

In the compressible flow class, only one project was developed to allow the students to get a hands-on experience in using the Low-Speed Wind Tunnel at the University of Dayton (Mini-Project 1). More projects for the compressible flow class are being conceived considering the current capabilities of the laboratory and will be offered in the next semester. The author found that incorporating hands-on projects was a great addition to the present teaching model which will be documented in detail in the follow-up paper.

## VI. Challenges in the Teaching Model

The current teaching model definitely came with some intransigence and challenges. The major feedback from the students was that portfolios were a lot of work even for a graduate class. Integration of class content from four classes, homework problems, independent studies and projects in each portfolio draft (which was due every two weeks) proved to be a Himalayan task for the students. Two students in the compressible aerodynamics class felt that the explaining the concepts taught in class in the portfolio didn't aid their understanding of the material while majority of the class found communicating the concepts they learned in their own words to be more effective than taking exams.

"I think it would help students and reduce some of the burden of adding in class notes and related material in the portfolio itself. Students could then research and think about the applications discussed in class in a deeper sense or other applications not discussed in class, without thinking that they are potentially wasting time with the additional task of writing the class notes and integrating them into the portfolio. It's just a thought." - Hannah M

"I liked the portfolio method for teaching, but it sometimes felt overbearing. I try to be a perfectionist, providing the best effort on stuff that I do. I hope that is seen in this product at the end of the semester and can show how much I did learn over the course. I think it would be easier for future students to make this more entry based, maybe after a homework to write a portfolio entry. That way students can reflect on the important equations, yet provide a global perspective on the impact of the solution to the problem."

"Overall, looking back I really learned a lot during this course. We covered a wide range of topics which is demonstrated in the figure below. At first, it sounded like having no exams and just typing a portfolio would be easy. However, I would soon learn that it wasn't that simple. The portfolio was time consuming and took me between 15-25 hours a week, but it allowed myself and the other students to focus on the material. I did like how there was no additional stress over exams and specific problems to prepare for."

# **VII.** Conclusion

An integrated teaching model was practiced for the first time in a graduate compressible flow class at the University of Dayton. The intention of the presented teaching model is to change the conventional way of teaching graduate classes by taking the focus from deriving the equations and connecting the equations to applications. Five major skillsets inspired from EFF standards were incorporated to the teaching model which are

- 1. Application of the concepts to real world
- 2. Solving open-ended problems
- 3. Critical thinking
- 4. Independent research
- 5. Technical Communication

Learning objectives for the class were conceived for the students to achieve all five skillsets. The portfolio was used as a platform for the students to show their progress in all five skillsets. Emphasis was given on the reflections and the feedback. Several teaching modules were practiced in the class to change the traditional lecture based classroom setting. Students feedback on the proposed teaching model was crucial to the author in determining the advantages and disadvantages of the teaching model. While there are many advantages to the proposed teaching model when compared to the traditional lecturing model, one drawback is that the workload of the students and the instructor was significantly increased. The author is taking appropriate measures to reduce the workload of the students and the instructor while maintaining the same learning objectives. A second trial of the teaching model is being practiced in the Fundamental Aerodynamics class which will be documented in the follow-up paper.

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# APPENDIX

AEE 553 Compressible Flow Mechanical and Aerospace Department University of Dayton

# Homework 1

## Due: Thursday 9/8/2016

Dear students,

Once again, welcome to the Compressible flow class. The idea behind this homework is to make you think about some of the introductory concepts covered in the first two classes. You can turn in this assignment separately or you can tie it in as a part of your portfolio. This homework is intentionally abstract and open ended as advertised in the syllabus. Once you practice doing these kind of problems, I strongly believe that you will become better thinkers and learners. Always remember that I don't care much about you getting the "right" answer. I care more about the approach you take to solve a problem. So focus on the approach.

#### **Question 1 (15 points)**

For all the different flow regimes discussed in class (incompressible, transonic, supersonic, hypersonic), select an airplane which flies in those regimes and discuss their design. Why do you think those airplanes look different? What is the driving the design of the airplane as you go faster? You can use pictures, cartoons, graphs, annotations, etc. to explain your answer.

#### Question 2 (10 points)

Discuss why we should not use Bernoulli's equation while dealing with compressible flow. Why or what makes it invalid to be used compressible flow? You can use pictures, derivations, equations to explain your answer.

#### **Question 3 (10 points)**

For all the airplanes you discussed in Question 1, determine the temperature increase they experience while cruising. Based on the values you obtain, why do you think it is reasonable exclude energy equation in incompressible flow and not in compressible flows?

#### Question 4 (15 points)

I am sure you have all heard of the joint jet fighter F-35. As you know, it employs a unique thrust vectoring capability to be able to take off vertically. Using equations of fluid flow, <u>algebraically</u> show the variation of airplane's lift and thrust as a function of thrust vectoring angle. Show the appropriate control volume clearly. 10 extra-credit points will be awarded if you plot the variation of lift and thrust as a function of thrust vectoring angle.



## **Homework 2**

#### Due: Thursday 9/15/2016

Dear students,

In this assignment you will perform a control volume analysis and apply continuity, momentum and energy equations to solve a very interesting open ended problem. The result of this problem is of high significance in compressible flow. All the homework in this class plays an integral part in your learning of the subject. Think of all the homework as pieces of a large puzzle. As such, apart from solving this problem, it is VERY important that you include the work you are doing in the homework as a part of the narrative in your portfolio.

Consider you are an officer operating in the US NAVY in the 1920's, the time when the theories of compressible flows were not fully established yet. You hear intel that a US submarine which is temporarily surfaced due to technical issues approximately 50 nautical miles from the coast of San Diego will be attacked in an hour. All the radar and satellite communication systems are down and the only way you can alert the submarine is through the Emergency Alert System (EAS) using a weather deck megaphone and through the Underwater Warning System (UWS). These systems run on independent power grid and you are aware that you only have enough power to operate just one system. You have to choose which system to use to send signal to the submarine as SOON as possible so that they are aware. Your weather gage reads that the temperature of the air is 10°C and the temperature of ocean is 15°C.

You realize that you have to calculate the time it would take for the emergency signal from EAS and UWS to reach the submarine because every second counts. How do you do it? Based on your answer, which system would you use to send the emergency signal to the submarine?

You are aware that you have to use equations of fluid motion (continuity, momentum and energy) to calculate time it would take for the emergency signal to reach the submarine. You can assume the air to be ideal, isentropic, isothermal and adiabatic. State where you use these assumptions.



# **Homework 3**

# Due: Set an appointment with me to present your results on or before 9/25/2016

Dear students,

In this assignment, you will be using the concept of critical Mach number to solve another very interesting open ended problem. By doing this assignment you will have a taste of what it is like to be an airplane designer. Hope you come to a realization of how the equations we learn in class are used in real life on a day to day basis to design airplanes. In this assignment, you may have to use low order simulation software such as XFOIL or XFLR5.



Assume you are working as a design engineer in Boeing. Since at least 2012, Boeing has identified a gap in the market between the single-aisle 737 Max 9 and the twin-aisle 787-8. A two-year series of discussions with customers revealed a consensus for an aircraft with about 20% more range and payload than a 757-200. Therefore the company is currently starting to design a new airliner aimed to fill this "middle of the market" (MOM) niche. You are a brand new recruit by the company and you have to impress them through your work. Since designing and manufacturing a supercritical airfoil takes time and money, your project manager asks you to find an existing airfoil that can be used in the new airliner which will allow the airplane to cruise FASTER in the transonic range. He says you have to report back to him within two weeks.

You realize that you have to compare a minimum of three different airfoils: One with high thickness, one with medium thickness and one with low thickness (you are free to choose any airfoils in these categories) to convince your boss of your choice. Out of these three airfoils, you have to find out one airfoil which has the ability to fly faster at transonic speeds without significantly increasing the drag of the airplane.

How do you find the Mach numbers that these airfoils can fly at without increasing the drag significantly and how does the answer relate to the thickness to chord ratio of the airfoil? Show appropriate equations, plots, annotations when you present your results to him in person. You don't have to write a report for this assignment. You will be evaluated by how well you present your results to your boss. You can make a powerpoint presentation or print graphs and equations. This is your first project in the company so you can't screw this up. Practice your spiel before you present your results.

# **Homework 4**

Dear students,

So far, you have learned how to determine velocity in incompressible flow and subsonic compressible flow. In the first question of this assignment, you will be using the normal shock relations to figure out how to determine velocity in a supersonic flow! In the second question, you will be using your knowledge of normal shock relations to solve a very interesting design problem!

#### **Question 1**

Consider the Pitot - static system in the F-16 airplane shown below. Assume that the airplane is cruising at its service ceiling of 50,000 ft. Determine the

- 1. Mach number at which the airplane is flying
- 2. The strength of the shock wave at the stagnation point
- 3. The temperatures at the static and stagnation ports
- 4. And the shock angle emanating from the nose of the airplane

for the following two scenarios:

- 1) The stagnation port at the nose of the airplane reads 122 kPa and the static port reads 100 kPa
- 2) The stagnation port at the nose of the airplane reads 300 kPa and the static port reads 20 kPa



## **Stagnation Port**

## **Question 2**

If the stagnation port is made of Aluminum, at what Mach number will the stagnation port melt?!

# **Homework 5**

## **Due: Along with Portfolio 3**

#### Dear students,

I am very sorry I could not teach today. I was usurped to attend a meeting with a legal department regarding getting a Green Card (permanent residency) during the time of our class. Apparently the person I am supposed to meet come to campus only once a semester. But you guys can still have fun without me! I thought you can practice some of the problems (4 questions) mentioned in this handout which should make you think more about what we learned so far. And research on some of the topics we discussed when you met me for HW 3 discussion. You can include the work you did in your portfolio draft 3.

### Question 1

Do an independent study on the following areas and see how it connects with what we learned in class or what you learned in your homework -

- Supercritical Airfoils
- Effect of Sweep
- Area Rule for Airplanes
- Below is a picture of Convair 990 airplane. Find out what these are



#### **Question 2**

What happens to Mach number behind a normal shock as the Mach number upstream increases without limits? Consider a normal shock wave at a Mach number of 2, 4, 6, 8 and 10. How does the Mach number behind the normal shock change? Is there a trend?

### **Question 3**

Consider the F-16 airplane from scenario 2 of the first question from HW 4. How long after the airplane passes directly over you, you will hear the sonic boom?

### **Question 4**

At an altitude of 50000 ft, F-16 accelerates from Mach 0.5 to Mach 2. What pressure should the Pitot tube read as a function of the acceleration? And if a thermocouple is placed at a stagnation port, what temperature would it read throughout the acceleration?

# Homework 6

## **Due: Along with Portfolio 4**

Dear students,

In this assignment, you will use the knowledge you gained on the oblique shock and expansion waves to solve a very cool problem.

### **Question 1**

Some of the supersonic airplanes such as F-104 shown below has what is called a diamond shaped airfoil.





Consider the F-104 is flying at Mach 2. And the half wedge angle of that wing is  $10^{\circ}$ . The question is simple! Find the lift generated by the diamond airfoil at an angle of attack of  $0^{\circ}$ ,  $5^{\circ}$  and  $10^{\circ}$ . Assume uniform pressure distribution across all areas of the surface.

## **Homework 7 - Nozzles**

#### **Due: Along with Portfolio 5**

Hey guys,

Continuing our fascination with nozzles, in this homework, you will get to use some of the concepts and equations we learned in class about nozzles. There are two parts to this assignment. The first one involves subsonic nozzles involving UD-LSWT and in the second part you will use the parameters for the Space Shuttle Main Engines (SSME) to solve an interesting problem.

#### **Question 1**

Consider the contraction of our University of Dayton Low Speed Wind Tunnel. The area variation of the UD wind tunnel is given by,

Area  $(x) = 0.2203 x^5 - 2.4664 x^4 + 8.7506 x^3 - 10.3960 x^2 + 4.2292 x + 0.25$ 



#### Assuming sea level conditions,

1. Determine the back pressure required to chock the inlet

2. Determine the inlet velocity for the chocked condition

3. Assuming chocked conditions, plot the variation of static pressure and Mach number as a function of inlet length

4. If the exit velocity is M = 0.8, plot the variation of static pressure and Mach number as a function of inlet length

#### **Question 2**

The specifications of the Space Shuttle Main Engines (SSME) is shown below

- 1.  $A_{entry} = 0.21 m^2$ 2.  $A_{throat} = 0.054 m^2$ 3.  $A_{exit} = 4.17 m^2$ 4.  $\gamma = 1.2$ 5.  $T_{entry} = 3,600 K$ 6.  $Q = 494 kg s^{-1}$
- 7.  $P_{Chamber} = 204.08 \ bar$

## Using the parameters above,

1. Find the exit Mach number, exit velocity and thrust of SSME as a function of altitude (From sea level to 20 km above sea level).

2. Determine the "optimum" altitude of the engine.

3. Plot the "optimum" area ratio of the engine as a function of altitude from sea level to 20 km above sea level.



# Mini - Project 1

## Due: Tuesday 9/27/2016

Dear students,

This project consists of two parts. The first part is experimentation and the second part is computer simulation. The first part this project will expose you to wind tunnel testing and data analysis in which you will apply some of the concepts you learned in the class. You will be performing experiments at the University of Dayton Low Speed Wind Tunnel (UD-LSWT) and be learning to use Pitot-Static tube and other related equipment to estimate the tunnel speed. In the second part, you will also be exposed to XFOIL software in which you can do low order simulations to get numerous aerodynamic parameters.

## PART 1 Estimating Airspeed

Use the Pitot-Static tube available in the UD-LSWT and estimate the indicated airspeed, true airspeed, equivalent airspeed and calibrated airspeed at 100, 300, 500 and 700 RPM of the fan of the wind tunnel.

Assume the wind tunnel is on top of Mt. Everest!!! (how COOL would that be?? *Pun intended!*). What would be the indicated airspeed, true airspeed, equivalent airspeed and calibrated airspeed?

### PART 2 Simulating Pressure Coefficient

Simulate the pressure coefficient distribution on the upper and lower surface of the NACA 4412 airfoil at a Mach number of 0.6 using XFOIL. Pick any angle of attack. Apply all the compressibility correction methods you learned in class to the pressure coefficient and determine the corrected lift coefficient. Using the results you obtain, comment on the importance of compressibility corrections in airplane design.

# INTEGRATE THE RESULTS OF THIS PROJECT IN YOUR PORTFOLIO WITH PROPER NARRATIVE/EQUATIONS

(Not in an appendix but in line with the flow of the portfolio content. You can include your rough work in the appendix.)
 (Shade the narrative/results so that I can find the additions easily)

# **Rayleigh Flow**

## **Functional Relationships**

#### Hey guys,

Last class on Rayleigh flow was boring and was not inquisitive. So I thought we could approach this topic from an application standpoint. NASA is currently working on a turbine-less ducted fan shown below. We are going to learn to use Rayleigh equations to predict the flow parameters from Section 2 to Section 3. In this handout, we are going to use the conservation laws to predict the flow conditions at Section 3 upon heat addition after passing through the combustor.



Please go through the derivation as a group and make sure you understand the steps involved. Also, fill out the missing steps in the derivations.

Let the addition of heat dq change the properties of the flow by infinitesimal amount as a function of combustor length. Assume the velocity of the flow has changed due to the heat addition by dV. Then, we can relate:

#### I. Changes in density due to changes in velocity: (Continuity)

$$\frac{d\rho}{\rho} = \tag{1}$$

#### **II.** Changes in pressure due to changes in velocity:

From conservation of momentum:

$$dP = - \tag{2}$$

Dividing *P* throughout Equation 2

$$\frac{dP}{P} = -\frac{\rho}{P} \, V dV \tag{3}$$

Equation 3 can be written as, (Fill in the steps in between)

$$\frac{dP}{P} = \tag{4}$$

#### **III.** Changes in temperature due to changes in velocity:

From ideal gas law,

$$\frac{dT}{T} = \frac{dP}{P} -$$
(5)

From Equation 4 and continuity equation, (Fill in the steps in between)

$$\frac{dT}{T} = (1 - \gamma M^2) \frac{dV}{V}$$
(6)

#### IV. Changes in Mach number due to changes in velocity:

From Mach number relation,

$$M =$$
(7)

Differentiate Equation 7,

$$dM = \frac{dV}{\sqrt{\gamma RT}} -$$
(8)

You should get (Fill in the steps in between)

$$\frac{dM}{M} = \frac{dV}{V} -$$
(9)

Substitute Equation 6 in Equation 9,

$$\frac{dM}{M} = (\qquad)\frac{dV}{V} \tag{10}$$

# V. Changes in total temperature due to velocity

From energy equation,

$$T_0 = T + \tag{11}$$

Differentiate Equation 11,

$$dT_0 = dT + \tag{12}$$

(Fill in the following steps)

$$dT_0 = T (1 - M^2) \frac{dV}{V}$$
(13)

We know,

$$T_0 = T\left(1 + \frac{\gamma - 1}{2}M^2\right) \tag{14}$$

Divide equation 13 and 14,

$$\frac{dT_0}{T_0} = (\qquad )\frac{dV}{V}$$
(15)

-

### **III.** Changes in entropy due to changes in velocity:

From second law of thermodynamics,

$$ds = C_p \ln\left(\frac{T+dT}{T}\right) - R \ln(\qquad) \tag{16}$$

Simplifying,

$$ds = C_p \ln\left(1 + \frac{dT}{T}\right) - R \ln(q_{1})$$
(17)

Using Taylor series,

$$ds = C_p \left(\frac{dT}{T}\right) - \tag{18}$$

Substituting Equation 4 and Equation 6 in Equation 18, (Fill in the steps)

$$ds = \frac{dV}{V}$$
(19)

Now that we had established how changes in velocity results in changes in density, pressure, temperature and Mach number, lets rearrange the above equations to determine the changes in all those parameters as a function of changes in heat transfer (dq).

From energy equation,

$$T_{03} - T_{02} = \frac{q}{C_p} \tag{20}$$

In differential form,

$$dT_0 = \frac{dq}{C_p} \tag{21}$$

This shows that the heat addition and temperature are proportional to each other. If heat is added, total temperature will go up and vice-versa.

From Equation 15,

$$\frac{dV}{V} = (\qquad )\frac{dT_0}{T_0} \tag{22}$$

Now using Equation 22, you should be able to write the changes in density, pressure, temperature, Mach number and entropy as a function of changes in total temperature.

$$\frac{d\rho}{\rho} =$$
(23)

$$\frac{dP}{P} =$$
(24)

$$\frac{dT}{T} =$$
(25)

$$\frac{dM}{M} =$$
(26)

$$ds = \tag{27}$$

Changes in TOTAL PRESSURE as a function of changes in total temperature:

From second law (considering the stagnation quantities),

$$ds = C_P \left(\frac{dT_0}{T_0}\right) - R \left(\frac{dP_0}{P_0}\right)$$
(28)

Substitute Equation 27 in Equation 28,

$$C_p \left( 1 + \frac{\gamma - 1}{2} M^2 \right) \frac{dT_0}{T_0} = C_P \left( \frac{dT_0}{T_0} \right) - R \left( \frac{dP_0}{P_0} \right)$$
(29)

Solve for  $dP_0/P_0$  (Fill in the steps)

$$\frac{dP_0}{P_0} = -\frac{\gamma M^2}{2} \frac{dT_0}{T_0}$$
(30)

Based on what you learned above, determine the variation in the parameters for different conditions. State whether the parameter increases, decreases or remains the same for the given conditions.

		Heat addition	Heat removal
Subsonic Flow	Density		
	Pressure		
	Temperature		
	Entropy		
	Mach number		
	Total Pressure		
	Total Temperature		
Supersonic Flow	Density		
	Pressure		
	Temperature		
	Entropy		
	Mach number		
	Total Pressure		
	Total Temperature		