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Design and Manufacturing of Nozzles and Airfoil Shapes for Compressible Flow Visualizations in a New Engineering Course

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Abstract

To empower students in engineering and improve their understanding of integrated computational design and experimental testing, the authors developed a new course for undergraduate engineering students. The course objective is for mechanical engineering students to gain an understanding of how airplanes fly and nozzles work by designing, modeling, manufacturing, and testing prototype airfoils and nozzles. These example problems are meaningful and attractive. The active, project-based learning approach promises better learning outcomes and outcome retention than passive approaches. The paper discusses the course structure including computer simulations and on paper calculations for the students, prototyping and manufacturing models from computer-aided design (CAD) representations, and experimental validation with a water table experiment. The planned course evaluation and assessment of student learning are presented. The course is taught at the University of California Davis in Spring Quarter 2017 for the first time.

Introduction

Mechanical and aerospace engineering are multi-disciplinary sciences. Many engineering topics and the principles behind them are sophisticated, so that real-world applications have to be based on theoretical concepts, numerical computer simulations, and experimental verification. Undergraduate students are usually presented with a lot of theory in their classes, but few applications, computer simulations and experiments and rarely all of these topics in a comprehensive, integrated course. In general, the engineering workforce is challenged because "interest in engineering is declining" and "women and minorities are significantly underrepresented in engineering" (NSF Engineering Task Force, 2013). Three professors at the University of California Davis from manufacturing, thermos-fluid dynamics, and education have developed a new class that will address these needs in three core ways.

First, the new course is authentic to contemporary needs within the engineering industry. The course integrates design, manufacturing, and validation within a coherent and meaningful set of activities. Although these engineering skills overlap in industry, they are typically isolated in students' undergraduate experience. Furthermore, the planned focus on efficiency and sustainability in the course is timely and important in industry, especially as companies and producers are becoming more responsible for their products (Allen et al, 2002, Haapala et al., 2013).

Second, the course takes an active, project-based approach that research shows is effective in fostering the development of deep, conceptual learning and, in turn, greater problem solving flexibility in engineering (Pandy et al., 2004; Rayne, et al., 2006). Experimental teaching approaches where students directly apply theories under study appears to result in better learning outcomes for capability and innovation (Taixiong et al., 2012). A combined materials/manufacturing processes course at Texas A&M University showed that students were excited by the class and performed equally well as the control class (Weinstein, 2003). More generally, hands on experiences, where students are allowed to try, fail, and iterate their understandings, are associated with the development of adaptive expertise – the ability to learn and adapt in the face of novel problems (Hatano & Inagaki, 1986; Schwartz, Bransford, & Sears, 2005).

Third, the course teaches engineering content in the context of a highly attractive context for young people: flight is a universally known, if sometime mysterious, feat of engineering achievement, there is growing awareness of and excitement about manufacturing techniques such as 3D printing and milling, and students are increasingly concerned with issues of environmental sustainability. Centering the course around these topics will not only generate excitement among students, but also create the opportunity for a more supportive learning environment. A substantial body of research in the learning sciences suggests that students learn best when they can bring in their existing understandings and beliefs about systems they are studying (National Research Council, 2000). The contexts of flight and sustainability allow for student engagement, while still presenting substantial opportunities for intellectual growth.

Course information

The new course is entitled “Design and Manufacturing Nozzle and Airfoil Models for Flow Visualizations” and is an additional elective course for mechanical engineering and aerospace engineering students. It has several courses as prerequisites (Figure 1). The prerequisites include a manufacturing process course, which teaches about different manufacturing technologies in general in lectures and machining processes specifically through hands-on workshop training. After this course, students have access to the student machine shop. For this course, students completed a course on Technical drawing and Computer-aided design (CAD). Another prerequisite is a Thermo-Fluid Dynamics course which teaches about inviscid incompressible flow, compressible flow, ideal gas mixtures, psychrometrics, reacting mixtures and combustion. Before taking this class, students completed courses on fluid mechanics (fluid properties, fluid statics, continuity and linear momentum equations for control volumes, flow of incompressible fluids in pipes, dimensional analysis and boundary-layer flows) and thermodynamics (fundamentals of thermodynamics: heat energy and work, properties of pure substances, First and Second Law for closed and open systems, reversibility, entropy, thermodynamic temperature scales).

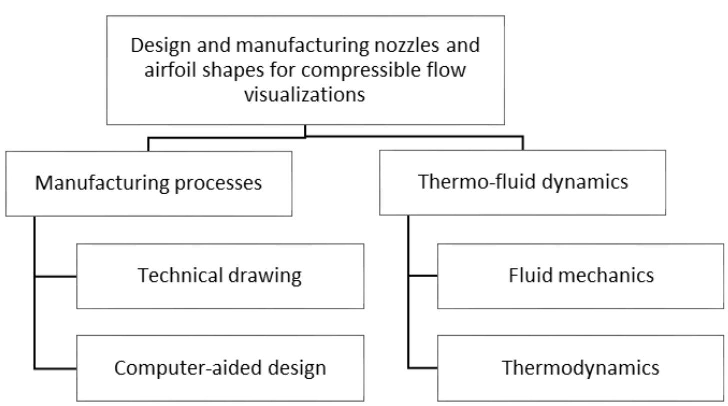

Figure 1: Prerequisites

Course summary

The course content is discussed here and includes an introduction to flight, fluid flow, the water table experiment and simulation, and the model shapes. For the first time the class is offered, the class will be taught twice weekly, with Professor Linke, who is the manufacturing expert, teaching the first half of each day and the second half of each lecture being covered by Professor Hafez, who is the aeronautical science expert (Table 1). The alternation between professors will ensure that all topics are taught concurrently and student interest is kept high.

Table 1: Class schedule

Week	**Lectures Prof. Linke, 12.10 – 1.00 pm, Tuesdays and Thursdays**	**Lectures Prof. Hafez, 1.10 – 2.00 pm, Tuesdays and Thursdays**	**Homework assignments and project deliverables**
1	Review of manufacturing processes and process planning	Review of fluid mechanics and thermodynamics	
2	Airfoil and nozzle design and manufacturing	Review of compressible flows including nozzles at design and off design conditions	Process plan for simple shapes
3	Manufacturing performance indicators	Prandtl Meyer expansion fans	CAD drawing, geometric dimensioning and tolerancing
4	CAD/CAM	Oblique shock waves	Relations of Prandtl Meyer expansion fans
5	Costing	Euler Equations and Conservation Laws	Relations of oblique shock waves
	Joint Review		
6	Sustainability	Shallow Water Theory and its limitations	Costing and sustainability factors
7	Product quality (dimensions)	Hydraulic Analogy and its limitations	Correspondence between Mach and Froude number
8	Product quality (roughness)	Computer simulations	Test plan for water table experiments and computations
9	Industrial change management	Water Table Experiments	Updated CAD drawing and change request
10	LCA of efficient airplane wings	Comparison between experimental and computational results	Results for water table experiments
	Joint Review		

Homework and project assignments are due weekly and cover manufacturing, design and thermo-fluid dynamics. The teaching assistant/s will have office hours with access to the water table later in the quarter so that students can access the table and conduct tests for the project.

Airplanes fly because their wings cause a lift force when air flows past the wings. In addition to the lift force, the flying airplane experiences thrust, drag, and weight forces (Anderson, 2001). The wing cross-section perpendicular to the wing leading edge is called airfoil and needs to be designed carefully for maximum performance (Sforza, 2014). The amount of lift generated by an object depends on the quantity of fluid that changes direction, which depends on the shape of the airfoil body. Airfoils can be considered a 2D problem in thermo-fluid dynamics, whereas nozzles are simplified as a quasi-1D problem, where the airflow is symmetric and only varies along the nozzle main axis. Nozzles are important in many engineering applications including rocket design.

Depending on airfoil and nozzle design, shock waves, i.e. nearly discontinuous changes occurring in supersonic flow, appear. Since airfoils and rocket nozzles operate in local flow velocities that are close to the speed of sound (transonic region), air flow behavior has to be studied as compressible flow. The studies of compressible flow are more complicated than of incompressible flow, as taught in the prerequisite classes. Therefore, students will learn about the thermo-fluid dynamics of compressible flow that are necessary to design airplane wings and rocket nozzles.

Phenomena at airfoils and nozzles are usually studied in expensive and maintenance intensive wind tunnels. However, the Hydraulic Analogy describes that shallow water behaves similar to air. Water height relates to air density and temperature. In a simple water table experiment, a model with the cross-section to be studied is pulled through a thin water layer (Figure 2). The shock wave pattern in water matches the pattern in air. In this course, water table experiments will be used to demonstrate and visualize the physical phenomena. Furthermore, simplified analytical calculations for simple shapes and computer calculations for more complicated shapes will be used to predict shock patterns (Figure 3). To study the two-dimensional steady compressible flow field in a nozzle and around an airfoil, the governing equations representing conservation laws of mass, momentum and energy are numerically solved with computers for the unknown variables of pressure, density and velocity components.

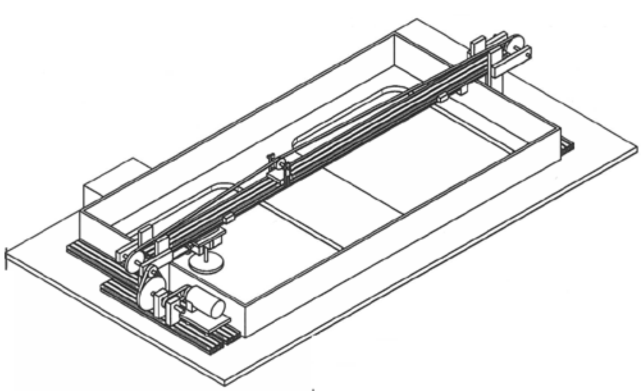

Figure 2: Left: Water table, Right: Biconvex airfoil model creates shock wave pattern

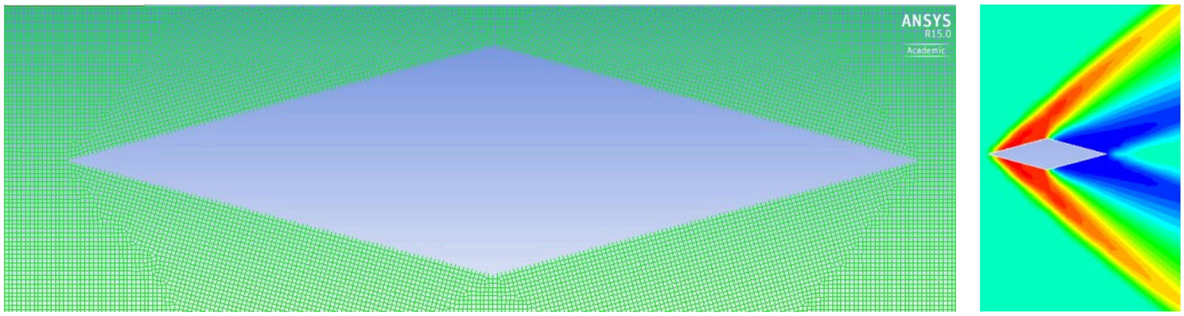

Figure 3: Left: Control volume mesh around a diamond wedge, Right: Contour for the static pressure for supersonic diamond airfoil at 0 degree angle of attack, created with ANSYS Fluent

A set of relevant model shapes (Figure 4) will be studied theoretically and physical models will be manufactured by the students. The students will learn about relevant manufacturing processes and product design procedures for airplane wings and nozzles and respective models. Selected additive and subtractive manufacturing procedures to produce models for the water table experiment will be studied in depth with regard to costs, quality, and sustainability. Sustainable manufacturing is an important topic with growing relevance, so the students will gain valuable expertise in this field. Furthermore, they fabricate models themselves and apply the learned principles.

Besides homework assignments that assess the technical knowledge and basic synthesis understanding, a group project will direct the students to integrate all course material by designing and analyzing airfoil or nozzle shapes, fabricating and testing models, and comparing computational and experimental results.

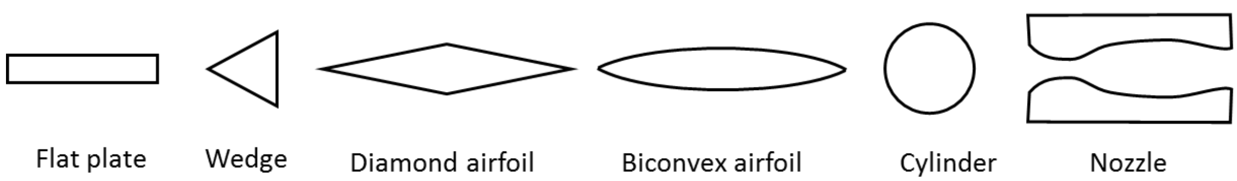

Figure 4: Relevant model shapes

Compressible flow theory

In the first week, the students will review fluid mechanics fundamentals, in particular conservation of mass as examined by Leonardo da Vinci, definition of pressure as derived by Pascal, Bernoulli's Law and Euler Equations, Newton Viscosity Law, and viscous effects and boundary layers. Furthermore, the basics of thermodynamics will be discussed: Perfect gas law (Boil, Charles, GayLusac, and Avogadro), First law of thermodynamics (Joule and Meyer), conservation of total energy (von Helmholtz), Second law of thermodynamics (Clausius, Max Planck, and Kelvin), entropy, and ideal processes and cycles. The second week covers a review of compressible flow including nozzles at design and off design conditions. The material consists of compressible flow fundamentals, in particular isentropic relations, speed of sound, Mach number, Mach angles, sound waves vs. shock waves, conservation of mass, momentum, and energy, and isentropic Euler equations. All these basics have been taught in the prerequisite courses. The third week deals with the Prandtl Meyer expansion fans. Algebraic relations will be derived in a homework assignment. The self-similar solution of the isentropic Euler equation is introduced. In week 4, oblique shock waves are discussed. The accompanying homework assignment will ask the students to derive algebraic relations.

The fifth week highlights Euler equations and conservation laws. Specifically, weak solutions of full Euler equations are introduced. In week 6, the shallow water theory and its limitations are discussed. This theory is important to fully understand the water table experiments. The governing equations of surface waves on a flat plate including conservation of mass and momentum and hydrostatic pressure equations are discussed. In contrast to an object in air, shallow water has a boundary to air so there will be additional effects to be considered in the water table experiments. In the seventh week, the Hydraulic Analogy and its limitations are detailed further. The isentropic Euler equations and the equations of waves on shallow water layer are compared. The homework assignment will explore the correspondence between Mach number and Froude number.

In week 8, computer simulations are introduced to calculate and estimate nonlinear and complex phenomena. The students will learn how grids are generated, finite difference schemes are applied, and numerical solvers are used. The ninth week will discuss the water table experiments for the following shapes: flat plate, wedge, diamond airfoil, biconvex airfoil, cylinders, and nozzles. In week 10, the experimental and computational results are compared for these shapes.

Sustainable Manufacturing

In parallel, students will be taught about industrial design and manufacturing processes with nozzles, airfoils and models for the water table as examples. In the first week, a review of manufacturing processes and process planning will define the general manufacturing process categories: primary shaping (casting, sintering, additive manufacturing, etc.), deforming (forging, bending, rolling, etc.), separating (milling, grinding, electro-discharge machining, etc.), joining (welding, soldering, seaming, etc.), coating (painting, laser cladding, etc.), and change of material properties (case hardening, annealing, etc.). Students will reiterate on the main objectives of process planning, such as reducing time and cost by e.g., minimizing setup steps, optimizing fixturing, jigs, clamps, reference planes or axis changes. A homework assignment will ask the students to generate process plans for example parts to test their technical knowledge. Furthermore, the students need to explain in 3 to 5 sentences why process planning is non-linear and complex, which assesses their understanding of the material.

In the second week, students will get an overview about different airfoil designs for small and commercial airplanes. Also different nozzle designs are reviewed, specifically converging and deLaval (converging-diverging) nozzles for rockets and turbo-machinery. Example production lines of lightweight rocket tubes, large rockets and air wings will be discussed with an emphasis on composite manufacturing.

In the third week, manufacturing performance indicators will be discussed in more detail. Productivity, quality and selected environmental parameters will be defined and connected with process parameters for a selection of additive and subtractive manufacturing operations that are applied to fabricate airfoil and nozzle models for water table testing. These operations include milling, water-jet cutting, laser cutting, and wire extrusion printing because they are available to the students in the student machine shop. The accompanying homework assignment will test if students can analyze surface roughness profiles and connect them with part performance in fluid dynamics applications.

In the fourth week, computer-aided design (CAD) and computer-aided manufacturing (CAM) will be emphasized. Students are already familiar with CAD and CAM from the prerequisite courses, and will learn more about the G-code commands, tool path planning and benefits and challenges from computer generated tool paths. Premade G-codes will be shown and discussed. The students have to produce CAD drawings for their student project.

In the fifth week, costing in production is presented. Time-dependent costs include costs for labor, machine use, energy and electricity, tool wear, and more. Time-independent costs include overhead, material, quality control, and more. Students will learn with case studies around model manufacturing. In week six, sustainability is introduced with the three dimensions: economy, environment, and society. The product life-cycle perspective is introduced. Furthermore, pollutants, embodied energy, and impacts on workers are discussed. Embodied energy describes the energy necessary to produce material and products including losses due to material extraction, manufacturing, transport, process inefficiencies, electricity generation, and more. The accompanying homework assignment will have the students calculate material and labor costs in a given scenario and reflect on additional costs and sustainability factors.

In the seventh week, product quality is reviewed in detail with regard to part dimension. Measurement frequency varies from 100% control in critical applications to statistical control in others, including Six Sigma. Various measurement devices, including a coordinate measurement machine (CMM) as present in the machine shop, are introduced. Week eight then tackles product quality with regard to surface roughness and topography. The standards for 2D and 3D parameters are introduced as well as the most important measurement devices. A 2D roughness profilometer can be used for the models produced by the students in their project. In week 9, industrial change management is discussed. The concept and benefits of simultaneous engineering and the integration of design and manufacturing are introduced. Change reports are explained and used by the students in their student project. The tenth week closes with a life cycle assessment (LCA) of efficient airplane wings. This highlights the integration of design based on compressible flow theory, sustainability and manufacturing with an industrial example.

Student Project

The class project covers design, analysis, manufacturing, and testing of an airfoil or nozzle with specific requirements. Students need to conduct detailed analysis, prototyping, testing, and design iteration and present through a report, graphs, charts and tables. The project is offered as group project so students will be able to interact and discuss their ideas during the course.

First, the students propose a shape from the set of relevant shapes in Figure 4. The first project assignment will consist of drawing the shape as solid CAD model with two different dimensions. The second assignment will be to compute the shock pattern for different angles of attack. In parallel, the students need to fabricate their model. The models can be made with modest means, for example with foam board, plastic, wood or aluminum. Students have access to the student machine shop for this. The third assignment is a test plan for the water table experiments. The students will conduct first tests with their models and record the shock wave patterns. The fourth assignment has students revise their model shape, submit a new CAD drawing, and draft an engineering change request. The students can change the surface roughness (for example by manual sanding) and or the shape (by either fabricating a new model or adjusting the existing one). After changing the physical model and conducting more water table experiments, the fifth and last project assignment is submitted and includes the test results and comparison of measured wave patterns with predicted patterns. All work is reviewed and commented by the instructors.

Evaluation of the Course

Beyond the technical content, the course learning goals include that (1) theoretical and experimental results in engineering might differ, (2) successful engineering needs both analytical and empirical approaches, and (3) sustainable manufacturing includes multiple, sometimes contrasting and subjective criteria. The course and learning goals will be evaluated through several means (see Table 2). First, student learning will be assessed through examination of student work on homework assignments, exams, and project work.

Second, scenario-based assessment items will be used to evaluate if students are able to transfer their learning (following Walker et al. 2006). These will be specifically targeted to evaluate the benefits of the interdisciplinary nature of the instruction. Scenarios will require interdisciplinary thinking and application of concepts from fluid dynamics and manufacturing. Student responses will be scored based on the extent to which they draw upon and integrate these sources, and whether their ability to do so changes over time.

Third, students' perceptions of the class, their beliefs about engineering, and their beliefs about their own capabilities, will be assessed through self-report surveys. Students' evaluation of the class (course quality, self-report of learning, etc.) will be assessed through standard end of course evaluation questions. In addition, they will complete pre and post measures of on their perceptions of the value of engineering (the intrinsic value subscale of Li et al., 2008) and engineering design self-efficacy (Carberry, Lee, & Ohland, 2010).

Table 2: Evaluation plan

Evaluation Question	Instruments	Analysis/Timeline
Do students learn specific course content related to aeronautical engineering? To manufacturing engineering?	Classroom measurements (tests, quizzes, and written assignment)	Classroom measures will be analyzed formatively, during the course, to assess ongoing learning and to provide feedback to instructors and allow them to adjust instruction accordingly. These data will also be analyzed summatively, to evaluate the effectiveness of the course.
Are students able to apply their knowledge to related but novel questions? That is, can	Scenario-based assessment items developed by PIs.	Post-course. Scenario-based assessments will be qualitatively coded for the use of content and strategies learned from the course. Transfer of learning to novel

they show transfer of learning?		problems is considered a "gold standard" evaluation of learning by some educational researchers (Bransford, Schwartz, and Sears, 2005).
What are students' experiences of the classes?	Survey using standard "course evaluation" questions (e.g, quality of instruction, self-perceived amount of learning)	Post-course evaluation only. Data will be quantitatively summarized to provide a sense of students' perceptions and experience of the course.
Do students change in their views of engineering as a discipline and themselves as engineers?	Intrinsic value subscale from Li et al. (2008) Engineering design self-efficacy measure, Carberry, Lee, & Ohland (2010).	Pre- and post-course. These data will be analyzed quantitatively to look for shifts in student perceptions. We will also examine trends across any demographic groups large enough to analyze (e.g., gender)

Thus the course integrates concepts twofold, first both experimental and analytical design testing and second manufacturing implications on design. And thus, a hypothesis is posited: students will gain a significant content knowledge in the course and will be able to transfer their knowledge to related areas; although it is uncertain if students will need support to do so. Students are expected to enjoy the integrated and applied course, and furthermore students are expected to raise their value perception of engineering. Similarly, students with low self-efficacy are expected to increase their self-efficacy, although this may interact with their growing understanding of the real work challenges that face engineers. The results of the adaptive expertise survey are expected to be small (based on prior research with the measure), but the result may be used as a covariate in analyses if significant variation is found across students.

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