2006-2048: INTRODUCTION TO AERODYNAMICS: A DESIGN/BUILD/TEST EXPERIENCE FOR UNDERGRADUATE MECHANICAL ENGINEERING STUDENTS

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Introduction to Aerodynamics: A Design/Build/Test Experience for Undergraduate Mechanical Engineering Students

Abstract

This paper presents the authors experience with a senior elective introductory course in Aerodynamics in the Department of Mechanical Engineering at Kansas State University. The course takes a hands-on experiential engineering design approach, loosely designated the "Wright Brother's approach" in which the students are introduced very early in the semester to relevant wing lift, drag, and pitching moment aerodynamic data obtained from wind tunnel laboratory testing. Throughout the semester, additional experiments are conducted and aerodynamic theory is progressively introduced to explain experimental results or to address necessary design issues as they arise. The course is further structured around a semester team design project in which students gradually develop their own airplane design (a glider model) based on the aerodynamic principles, and practical design topics, that are introduced throughout the semester. Subsequently, each design team constructs a working model of their glider design, and these models are flight tested at the end of the semester. Course topics introduced during the semester include basic wind tunnel testing and instrumentation, airplane stability and tail design, wing and fuselage design, basic propeller theory, and introductory numerical vortex panel theory, along with other topics such as wind tunnel design, bird flight and insect flight. The mix of practical hands-on design and aerodynamic theory that this course offers has been well-received by students.

Introduction

Aerodynamics represents an interesting and challenging course subject for undergraduate engineering students. It is closely related to aeronautics, which crosses over into many different disciplines of engineering including mechanical, electrical and electronics, controls, power systems and propulsion, heat transfer, and structural engineering. Applications of aerodynamics are also widely varied and diverse, including airplane design, automotive design, rocketry, and sailing, to mention but a few of the related areas that are touched by aerodynamic phenomena. To do justice to the subject invariably requires some significant attention to experimentation, not only to discover and demonstrate the associated aerodynamic principles, but to validate how well aerodynamic theory represents real physical characteristics. In an engineering program that includes a full aerospace program, this subject and the related topic areas would invariably be developed in a multiple course sequence. Doing justice to the subject of aerodynamics is particularly challenging when all the relevant topics must be focused into a single course, rather than part of a full aerospace program course sequence. The challenge is then to find the proper balance between the development of aerodynamic theory and laboratory application, with sufficient practical experience to make the subject more meaningful than a pure theoretical treatment would offer. The main objective of this paper is to present this authors experience with a senior elective introductory course in Aerodynamics, in the Department of Mechanical Engineering at Kansas State University, which appears to successfully meet this challenge.

Course Structure

The aerodynamics course discussed in this paper is typically taken by undergraduate Mechanical Engineering students in their last semester, and the prerequisites for the course are Undergraduate Fluid Mechanics and Differential Equations. The general course description is "***A general introduction to aerodynamics including the analysis of lift, drag, thrust, and performance of subsonic aircraft, and the application of aerodynamic principles to design.***" It is a three credit hour course taught in a 15-week semester format which meets three 50-minute periods each week. There is no formally scheduled lab time for this course; however, usually a total of four selected laboratory experiences are integrated into the class schedule. Typically several of the students that take this course are also involved with student organization projects such as the national SAE Aerodynamics Design Competition, and there are also occasional graduate students in the course.

Table 1 below illustrates the basic set of topics covered in the course, organized into the following three general categories: ***(1) Experimentation and Aerodynamic Analysis, (2) Aerodynamic Analysis and Design, and (3) Design and Aerodynamic Theory.***

Experimentation and Aerodynamic Analysis
- Aerodynamics—Historical perspective, aerodynamic forces, force/moment systems, standard atmosphere (1wk).
- Basic wind tunnel testing, dimensional analysis, lift, drag, moments (1.5 wk).
- Labs, airfoil lift, drag, moment, pressure distribution, aerodynamic center of wing-tail airplane, fuselage streamlining for drag reduction (2 wks).

Aerodynamic Analysis and Design
- Basic Principles of airplane design, glider performance and design, wing planform area determination, requirements for powered flight (2 wks).
- Moments and stability, center of pressure, aerodynamic center (1 wk).
- Bernoulli's equation, basic wind tunnel design, propeller theory (1.5 wks).

Design and Aerodynamic Theory
- Potential flow theory (stream function and velocity potential), Kutta-Joukowski theorem, thin airfoil theory (1 wk).
- Induced drag and finite wing effects (1 wk).
- Elementary vortex panel methods for numerical analysis (1 wk).
- Tapered wings, total airplane lift, drag, pitching moment (1 wk).

Other topics
- Exams (1wk).
- In-class design project discussion and related activities (1wk).

Table 1: General Layout of Topics in ME 628 Aerodynamics

The order and the duration of each of the identified topics is only approximate. There are three in-class exams and a take-home final exam which usually involves some element of numerical analysis using elementary aerodynamic theory such as embedded vortex or vortex panel analysis.

The course takes a hands-on ***experiential engineering design*** approach, loosely designated the "Wright Brother's approach" in which the students are introduced very early in the semester to relevant wing lift, drag, and pitching moment aerodynamic data obtained from wind tunnel laboratory testing. This data forms the basis for a step-by-step discovery approach to design, which results in the practical design of an airplane. Issues such as what comprises an airplane in the conventional sense. This initial design illustration is in fact patterned after a real airplane—the Piper Cherokee, a small propeller driven commercial aircraft. The design process is developed gradually, starting with a focus on the wing as the main lifting surface, and subsequently leads into a practical discussion of stability issues, as well as what distinguishes a so-called conventional airplane from more unusual designs.

Throughout the semester, additional laboratory experiments are conducted and aerodynamic theory is progressively introduced to explain experimental results or to address other important and necessary design issues. A more complete description of these laboratories is given in a separate section below. Toward the latter part of the semester students are introduced to more detailed aerodynamic analysis using basic "embedded vortex" or "vortex panel" numerical techniques. These techniques are developed from the concept of a single vortex filament, which is observed experimentally during one of the laboratories in the form of the wing-tip vortex flow structure. This filament concept is then combined with introductory inviscid flow superposition concepts to develop a numerical approach to airfoil analysis. The course is further structured around a semester team design project in which students gradually develop their own airplane design (a glider model) based on their understanding of the aerodynamic principles, and practical design topics, that are introduced throughout the semester. Subsequently, each design team constructs a working model of their glider design, and these models are flight tested at the end of the semester. Sessions outside of class are provided to give the students background in basic model building and construction techniques, including foam wing construction. These sessions are typically conducted by one or more of the SAE Aerodynamics Design Competition team members.

Laboratory Experiments

Wind tunnel (and water tunnel) experimentation, or at least reference to available experimental data, plays an important role in most any undergraduate course in aerodynamics. Measurements of the lift, drag and pitching moment behavior of airfoils as a function of angle of attack are a common occurrence in such labs. The importance of reinforcing theoretical aerodynamic concepts is clear, but the challenge is to provide meaningful experiments that demonstrate the desired effects without either introducing numerous extraneous phenomena, or overly complicating the experimental procedure.

When the focus is on airplane design, as it is in the ME 628 Aerodynamic course, longitudinal stability is also an important physical characteristic that requires investigation in the engineering laboratory. Here the pitching moment characteristics of airfoils and wing sections become of particular importance, along with determination of the aerodynamic center of the airfoil or wing section for comparison with established aerodynamic theory.

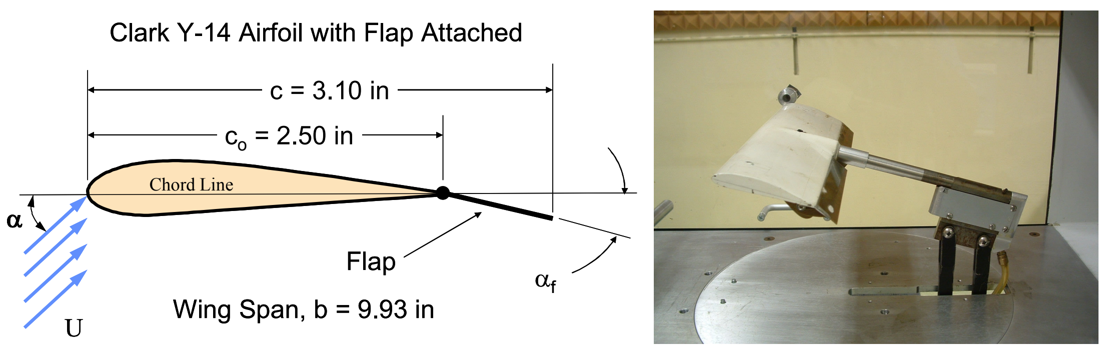
There are typically a total of four formal experiments conducted during the semester to demonstrate (discover) different aerodynamic principles. These are described below along with some illustrations of the associated experimental facilities.

(a) Wind Tunnel **(b) Test Section with Drag Model**

Figure 1: Wind Tunnel Test Facility

Lab#1: Basic Wing Lift, Drag, and Pitching Moment Characteristics

Figure 1 shows a photograph of the Educational Wind Tunnel used to conduct the aerodynamic testing for the ME 628 course, along with a close-up of the test section. The wind tunnel has a test section measuring 12 in x 12 in x 24 in (305mm x 305mm x 610mm), and has a maximum air speed of approximately 140 mph (63 m/s). It is instrumented with an electronic strain-gage based balance for measurements of normal force, axial force, pitching moment, and pressure distribution as a function of air speed and angle of attack. Manual measurements are accessible from a front panel digital display, and electronic data acquisition is also available for remote access and real-time measurements. A close-up photograph of the interior of the test section and sting, with a flapped wing configuration mounted, is shown in Figure 2. This particular wing section has a Clark Y14 airfoil cross-section, with a 0.60 in trailing edge flap for investigating the effect of airfoil camber on wing lift, drag, and pitching moment characteristics.



(a) Airfoil Geometry **(b) Wing with Flap**

Figure 3: Wing with Trailing Edge Flap

Using the data collected for this wing, and principles of dimensional analysis typically introduced in undergraduate fluid mechanics, the students "discover" experimentally the relationship between coefficients of lift, drag, and pitching moment, as a function of flap angle, airspeed, and angle of attack. They further discover the onset of "stall," which effectively defined the useful (approximately linear) operating range of the coefficients as a function of angle of attack. In addition, the center of pressure and the aerodynamic center (point where the pitching moment is constant and independent of angle of attack) can also be determined. From the center of pressure behavior at the onset of stall, it becomes clear that there is a rapid redistribution of the pressure difference across the airfoil; although at this point they do not know the specifics of what is happening or where. The aerodynamic center is introduced as a means of resolving a difficult issue with regard to the moving balance point for the effective lift force location (center of pressure), which is important when considering airplane stability.

Lab#2: Wing-Tail Airplane Aerodynamic Center

Practical airplane or glider design also requires selection of an airplane configuration, which typically involves wing and tail aerodynamic surfaces. In class the need for this airplane configuration is introduced in an effort to both establish the angle of attack necessary for maintaining steady level flight, as well as to provide the necessary longitudinal stability. The airplane configuration could be either that of a conventional airplane with the wing in the front and the tail behind, or a canard arrangement with the wing and tail positions reversed. In either case, it now becomes necessary to consider the overall stability of the entire airplane. Airplane stability issues are first analyzed theoretically in class, and then demonstrated in class by means of a simple and inexpensive balsa glider model shown in Figure 4 below.

1. "Weight" (mass) Information
Fuselage mass = 7.3 grams

Horizontal stabilizer mass = 1.1 grams

Wing mass = 3.0 grams

Total mass = 11.4 grams

2. Wing Characteristics
Planform Area = 24 in^2

Wing AR = 6

Wing Chord = 2.0 in

Wing Span = 12 in.

3. Horizontal Stabilizer Characteristics:
Planform Area = 6.5 in^2

Span = 5.5 in

AR = 4.6

Tail incidence angle = 5 degrees
(Note: Incidence angle is negative)

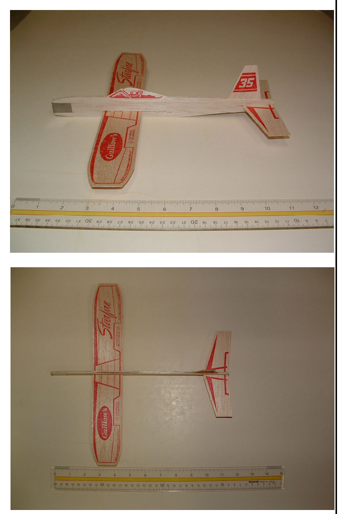
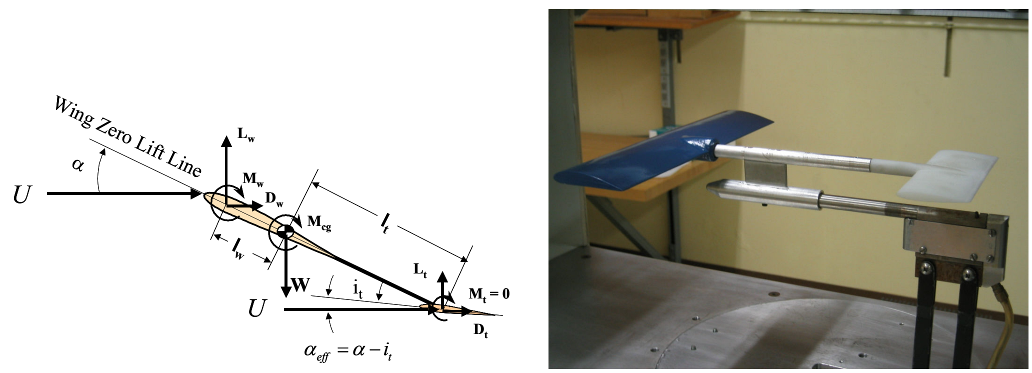


Figure 4: The "Starfire" Balsa Glider

Students are introduced to simple longitudinal stability theory, which takes the form of a so-called "area-balance" relationship, in which the wing planform area and the tail planform area together form a kind of fulcrum about the balance point. This balance point is the "neutral point, or aerodynamic center of the entire airplane. For stability, it is shown that the center of gravity must be in front of the neutral point. From this simple relationship, various configurations of the Starfire glider are demonstrated and verified by testing in class. These include the canard configuration with the tail in front of the wind, and a wing only configuration. The canard configuration also provides a means of introducing lateral stability issues as well, since simply turning the airplane around and making the airplane longitudinally stable does not make it fly well. The students discover experimentally that it is also necessary to shift the vertical tail to the rear of the canard to also prevent lateral instability (roll).

For the second lab, an innovative modular airplane configuration has been developed which consists of an interchangeable wing and horizontal tail configuration that mounts on a conventional wind tunnel electronic balance ("sting") to enable easy measurements of normal force, axial force and longitudinal pitching moment. This simple system facilitates the experimental investigation (and verification) of the characteristics of wing-tail airplane longitudinal stability through measurement of the aerodynamic center position of the "***entire airplane***" from measurements of normal force and leading edge pitching moment as a function of angle of attack for a selected combination of wing and horizontal tail. Figure 5 shows one of the typical wing-tail airplane configurations available, along with its simplified force-moment diagram.



(a) Force Moment Diagram **(b) Mounted Wing-Tail Airplane**

Figure 5: Wing with Trailing Edge Flap

The aerodynamic center position is determined from the experimental results and subsequently compared with a prediction from the simple area balance aerodynamic longitudinal stability theory introduced in class [1]. Agreement between the measurements and this simple theory is quite good, and also provides evidence of the influence of "downwash" on the stability characteristics of the airplane due to the wing-tip vortex system. In particular, the measured aerodynamic center is observed to be behind the theoretical location, indicating that downwash due to the wing-tip vortex system reduces the effective size of the tail (and hence reduces stability).

In addition to the quantitative measurements leading up to the determination of the aerodynamic center, flow visualization is used to "discover" the wing-tip vortex system responsible for the downwash and subsequent influence on the horizontal tail. Figure 6 shows the water tunnel facility and a close-up of the simple inverted wing model used to demonstrate wing-tip vortex flow downstream of the wing tip.

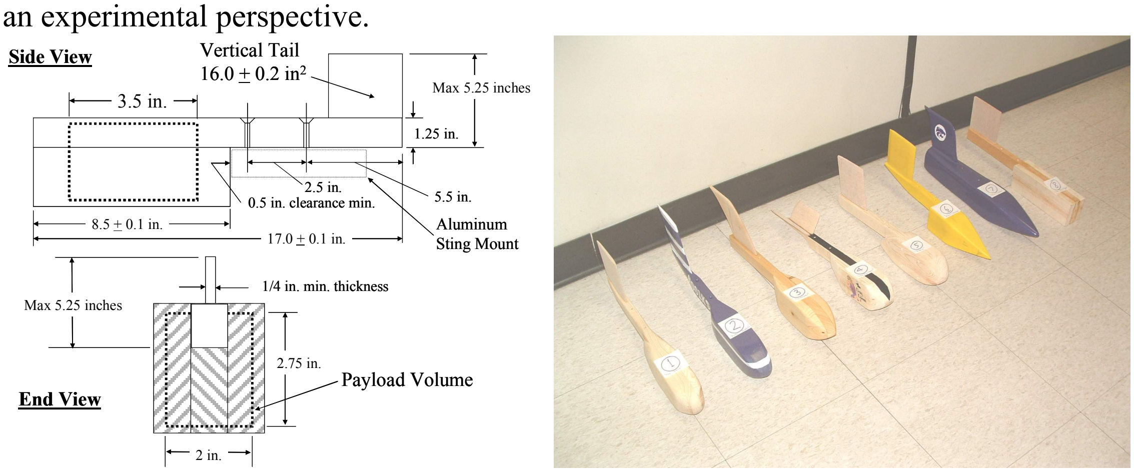
(a) Table-Top Water Tunnel (b) Water Tunnel Test Section

Figure 6: Water Tunnel Test Facility

Dye injection makes the vortex visible, and the influence of angle of attack is also investigated. Students can also see that the direction of vortex rotation can be controlled by means of the angle of attack. This reinforces the concept of a localized vortex filament, which is important not only for explaining and predicting the downwash effects on horizontal tail, but in introducing thin airfoil theory for predicting the airfoil pressure distribution and pitching moment characteristics. It furthermore provides a take-off point for explaining downwash on the wing itself, and subsequently a simple theory explaining the reduction of lift (and the existence of drag due to lift, or induced drag) as well as the effect of aspect ratio for a finite wing.

Lab#3: Drag Reduction by Streamlining

In the third lab, the concepts of drag reduction through streamlining are introduced, again from an experimental perspective.



(a) Fuselage Design Constraints (b) Ranked Fuselage Designs

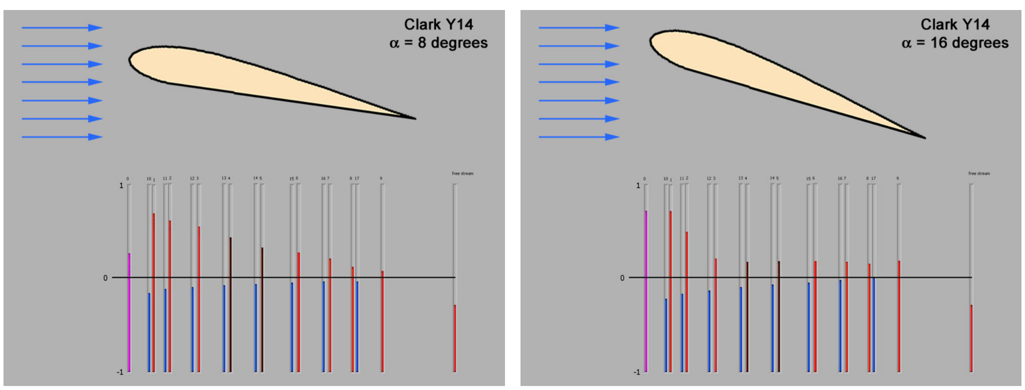
Figure 7: Fuselage Mini-Design, Build, Test Lab to Investigate Streamlining

Students are given the task of minimizing the drag due to a simplified fuselage model, which has payload compartment design constraints similar to the design constraints for their semester glider design project. The basic configuration of this fuselage is shown below in Figure 7, along with fuselage designs developed by the students ranked in order of increasing drag coefficient from left to right. The "box' design to the far right corresponds to no attempt at streamlining.

As part of the design process, and prior to testing in the wind tunnel, students are asked to provide an estimate of the drag coefficient and the resulting drag force as a function of airspeed. They must also provide a basis for their design or a design concept. This requires them to refer to their fluid mechanics background, as well as other available published information on streamlining, to determine a design concept and an approximate drag coefficient. The lab demonstrates that streamlining must focus on the trailing edge of the model to achieve minimum drag, and not just the leading edge which is the common misconception. The range of drag coefficients is usually observed to be nearly a factor of two. This lab also provides a baseline of data for their semester glider design project.

Lab#4: Airfoil Pressure Distribution

In the forth lab, the students obtain pressure distribution measurements at selected angles of attack for a Clark-Y14 airfoil test section, which is mounted vertically in the AEROLAB Educational Wind Tunnel test facility. They then use these test results to determine the pressure coefficient distribution for several selected angles of attack and two different air speeds. They also have an opportunity to see measurements of the pressure distribution on the same airfoil at various angles of attack using our multi-sensor electronic pressure scanning valve system. This data forms the basis for subsequent theoretical comparisons with simple thin airfoil theory discussed below. Figure 8 shows a comparison of the pressure distribution indicated by an electronic monometer bank displayed in LabVIEW with the angle of attack of the airfoil. The left figure corresponds to well below stall, while the right-hand figure is near stall.



(a) Well-Below Stall **(b) Near Stall**

Figure 8: Airfoil Pressure Distribution Measurements

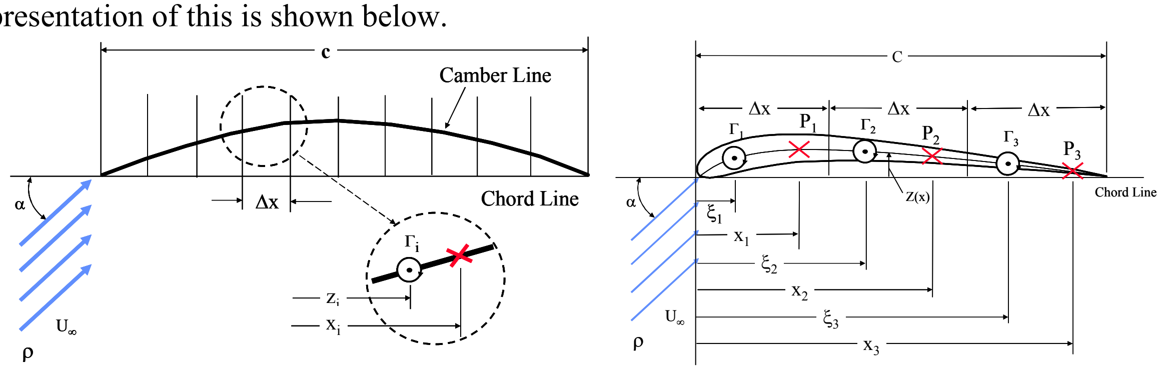
The students can see the approach to stall and now have a more detailed view of what happens to the pressure distribution—explaining the earlier results obtained in Lab#1 from the sting measurements.

Introductory Aerodynamic Theory

Very near the beginning of the course the first lab is used to introduce students to the basic aerodynamic parameters. Using data acquired in this lab, aerodynamic theory is progressively introduced and focused to achieve the design of an actual airplane—the Piper Cherokee. The issues connected with this design, namely the design constraints and desired performance in steady level flight, form the basis for initiating the design process. This leads naturally to a discussion of stability in steady level flight, and the need to provide by means of a tail the required attitude of the airplane. It is further observed that the stability issues connected with the determination of attitude in steady level powered flight are similar to those associated with a glider in steady glide.

The text used in this course is ***Introduction to Flight*** by John D. Anderson [2]. This book is one of the introductory course texts used in a typical aerospace program curriculum. While it does not provide an in depth treatment of either experimentation or aerodynamic theory, it provides a broad treatment of the overall subject with emphasis on flight. In particular, it provides a firm foundation in basic aerodynamic stability principles which is very important for the focus of the present course on design. Supplementary material is provided to address measurement and instrumentation issues connected with the wind tunnel measurements. One of the problems in some treatments of aerodynamics from primarily a theoretical perspective is that the students do not get a good physical feel for the practical application of theory, the accuracy with which theory can represent experimental results, and the reasons or motivations for the measurement and prediction of the typical aerodynamic coefficients of lift, drag, and pitching moment in the first place.

In addition to the basic stability theory introduced in class, thin airfoil theory is later also introduced to explain from fluid mechanics principles the early lift and pitching moment observations in the first lab. The simplest of these is the so-called “embedded vortex” theory, in which the lift is presumed to be “localized” at discrete locations distributed along the camber line of the airfoil. This theory follows directly from the classical Kutta-Joukowski Theorem of lift, in conjunction with the concept of an embedded (or bound) vortex within the wing. A schematic representation of this is shown below.



(a) General Embedded Vortex Concept **(b) 3-Segment Embedded Vortex**

Figure 9: Simple Embedded Vortex Theory for an Airfoil

This embedded vortex concept follows directly from the concept of a vortex filament introduced in earlier flow visualization related lab work. Using even a relatively few embedded vortices enables quite accurate calculation of both pressure distribution coefficient as well as pitching moment coefficient behavior. In particular, it enables a theoretical derivation of the airfoil aerodynamic center which then compares directly with the values determined in the earlier wind tunnel wing testing. This theory is introduced in the latter portion of the course to explain the more detailed measurements of the pressure distribution obtained in Lab#4. The analysis requires no more than the ability to solve a set of linear algebraic equations for the unknown embedded vortex circulation strengths. This in turn can be related directly to the pressure difference coefficients measured in lab. The analysis is easily accomplished by the students using either spreadsheets or other software such as Mathcad.

Other theoretical developments discussed in the class include a basic introduction of the so-called blade element theory of propellers. In this approach, the students are introduced to the basic ideas related to a propeller being a rotating airfoil and the fact that the air velocity "seen" locally by the propeller blade is deflected "downward" due to the forward motion of the propeller in flight. This combined with the use of the lift and drag data enables estimates of thrust and torque requirements. Once again this analysis is easily accomplished with only modest computational tools such as spreadsheets and Mathcad. Experimental verification of this theory is also being developed for additional and optional lab-related work associated with the course [3]. This simple theory can also be modified to include both axial and rotational momentum considerations for a more accurate treatment; however, this simple treatment serves well as a first introduction. The tilt of the air velocity due to the forward motion of the propeller is also used as a means to reinforce the concept of downwash associated with finite wing effects.

Glider Design Project

The ultimate application of the early experimental results, as well as the development of the underlying aerodynamic theory is the design, construction and flight testing of a free-flight glider. The early lab measurements provide a practical starting point for this design process, as is the case in other areas of engineering practice where theory requires time to catch up to the engineering of applications. A good example worth noting is the development of powered flight by the Wright Brothers, who achieved their successful flight in 1903, a year before Prandtl introduced the concept of boundary layer theory which opened the door to the practical theoretical analysis of fluid mechanics.

The design objective for the glider project is design, build and test a glider that will carry the largest payload from the launch position (at an elevation of approximately 20 feet) to the end of the launch field (a horizontal distance of approx. 200 ft). Design constraints include a specified planform area (approximately 350 square inches), and a required payload compartment equivalent in size to that used in the earlier Lab#3 mini-design, build, test exercise. A further requirement is that the glider must be hand launched and no active control onboard is allowed. Students are introduced to the analysis and design of gliders in class, and this analysis follows directly from the powered Piper Cherokee airplane design.

The students work in teams on this project primarily during the latter half of the semester, and each team is given a budget allowance of $50 to cover the cost of materials. Small kits containing basic construction supplies and cutting tools are also provided to each team. Foam cutting equipment is also made available for cutting wing sections; however, some teams use alternate construction techniques and materials including balsa. Some teams also elect to make their own hot-wire foam cutting setup, which is also relatively easy and inexpensive to do.

Figure 10: Examples of Glider Designs with Launch area in Background

Evaluation of the project consists of both a detailed design report, which documents the design process and analysis of performance, and flight testing which takes place in a rodeo arena on campus. This space is somewhat ideal for flight testing in that it is covered, heated and offers a virtually still-air environment even during winter the blizzard conditions which commonly occur in December at the end of the Fall semester.

Summary and Conclusions

This paper presents a novel “Wright Brothers” experiential approach to the teaching of an introductory senior level elective course in aerodynamics, applicable to a curriculum typical of mechanical engineering students. It is a single 3 credit hour course that introduces students to basic aerodynamic principles, including experimental and theoretical analysis. The course covers the basic engineering science topics relevant to aerodynamics, as well as an introduction to aerodynamic design principles, and basic principles of flight stability. Students also gain experience in wind tunnel testing and analysis of test results. Course topics introduced during the semester include basic wind tunnel testing and instrumentation, airplane stability and tail design, wing and fuselage design, basic propeller theory, and introductory numerical embedded vortex and vortex panel theory, along with other topics such as wind tunnel design, bird and insect flight.

One of the main challenges in this course has been to find the proper balance between aerodynamic theory, laboratory experimentation, and practical application to design, so as to accomplish a meaningful treatment of the subject in a single course. The mix of practical hands-on design and aerodynamic theory that this course offers has been well-received by students. This is somewhat evidenced by the fact that the number of students enrolling in this course has nearly doubled from on the order of twenty to most recently on the order of forty students in the past several years. Future plans include the development of a variety of mini-laboratory modules structured in a web-based format to supplement text information and to further reinforce the practical design process. A number of such mini-laboratory experimental setups are already available, and additional setups are being planned for construction using rapid prototyping technology.

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