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Aircraft Design for Second-year Undergraduate Students*

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As part of our department's 'learn by doing' curricular philosophy, and to help infuse design throughout our curriculum, we have evolved a sophomore-level programming course into an introduction to aerospace design course. The evolution has occurred over the past three years, as we have increasingly added design requirements to the course. We have found that sophomores can learn a great deal from designing a complex system with the use of software or semi-empirical design methods to supplement their lack of background knowledge. We have used new, innovative aircraft specifications to get the students to think about requirements, markets, and the importance of customer-based thinking in the design cycle.

INTRODUCTION

A DILEMMA has long existed in engineering curricula. Capstone design courses have been seen as just that—capstones. Students are required to complete large numbers of mathematics, science, engineering science, and program-dependent analysis courses before they 'complete' their education with design courses. In aeronautics, the progression has included background instruction in aerodynamics, stability and control, propulsion systems, and structures, with a supporting cast of coursework in mechanics, strength of materials, electronics, materials science, and social sciences and humanities. Unfortunately, the skills and abilities that make students successful in their analysis courses often do not serve them well in design courses.

While examining the literature and scrutinizing our curriculum, we found that the observations of Robert R. Furgason were very true:

> One continual comment, especially from employers, is that our engineering graduates are well prepared in the quantitative aspects of the scientific, mathematical, and engineering components of their education, but they often lack what we might term the 'soft' or 'people' skills; that is, the ability to communicate effectively—write, speak, and listen; the ability to work effectively in teams; an appreciation of the economic, environmental, safety, and social factors present in most settings that often dictate the approach that is used; and a realization of the political environment in which they work—both internal and external. In education, we stress the 'right answer' approach and our graduates do not have a good appreciation that most things we deal with are ambiguous and we seek best answers involving many subjective elements. Our curricula should be modified to incorporate these aspects into the educational process [1].

We also realized that students often don't see the importance and urgency of learning 'supporting' subjects until it is too late. A common undergraduate question is, 'I want to design airplanes; why do I have to take calculus/physics/mechanics/etc.?' And our answer is often, 'Trust me, you need to know calculus/physics/mechanics/etc. before you can design airplanes!' We sound like parents asking for blind trust, rather than mentors educating the students as to the importance of every subject in context. Only belatedly, when the students finally take design, do they understand the necessity for the long list of subjects in their curriculum. Regrettably, this revelation comes too late for some students who have 'slouched' their way through the supporting courses, but neither remember nor understand the subject matter. This approach leads to a great deal of inefficiency in many design courses, where design instructors have to spend countless hours on remedial work—providing instruction in subjects that students have already taken, but have not learnt or learned to apply.

The engineering industry and ABET have seen certain aspects of this problem and have consequently recommended that engineering programs incorporate design throughout their curricula. Industry wants graduates who are educated as aeronautical systems engineers, with an understanding of the following concepts: how an aircraft should be designed, how an aircraft should be built, and how the two relate to each other [2]. Engineering faculty, however, often have difficulty incorporating design throughout their curricula, either because they are more talented at analysis than design, or because they have little or no knowledge of what constitutes design. Their observation goes something like this: 'How can we teach

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them about design when they don't know about the basics?' [3]. Because these faculty see engineering coursework as preparation for graduate studies, they concentrate almost solely on analytic coursework and fail to imbue their students with a well-rounded view of engineering. In spite of some notable recent changes from this viewpoint [4], most faculty still adhere to a 'scientific' view of engineering, rather than embracing the totality of an engineering education. Hence, the dilemma: students don't see the connection between analysis and design until they've finished their design course, and faculty don't believe that design is possible until analysis coursework is completed.

The purpose of this article, and the curricular experiment that forms the basis for it, is to determine if there is an intermediate position between the two extremes expressed above. Is it possible to teach students 'about' design before they know a great deal about the analytical subjects that are necessary to 'do' design? We wanted to find out the answer to this question, and decided to use a sophomore second year programming course to initiate the students into the design thought process. In addition, the students could be exposed to a variety of professional practice issues, including working as a team, data collection and analysis, oral and written communications, market analysis, and ethical treatment of engineering decision making.

THE GENESIS OF A SOPHOMORE DESIGN COURSE

The faculty of the Aerospace Engineering Department at Cal Poly have long attempted to create a strong, vibrant aircraft design sequence for our students [5, 6]. The design course has progressed over the past fifty years from a course where students learned how to construct an airplane to courses where they perform detailed preliminary design of an aircraft, including many of its systems. This progression has been greatly enhanced by Cal Poly's participation in the NASA/University Space Research Association Program (USRA) and NASA's Aircraft Multidisciplinary Design and Analysis Fellowship Program (AMDAF), which enabled the department to give the students a more intensive aircraft design experience by allowing them to work on real-world design problems. Many of the aircraft design problems are industry-generated, with industry engineers actively involved in the department's instructional program via an advisory board. The board is made up of approximately twenty engineers and engineering managers from a cross-section of the aerospace industry. They supply the support, both financial and technical, which makes our design course successful.

The senior-level aircraft design curriculum at Cal Poly is a well-integrated, intensive, year-long course, requiring prerequisite knowledge in aerodynamics, flight performance, and aircraft structures as well as concurrent knowledge in gas dynamics, propulsion systems, and stability and control. The course included introductory information on aircraft sizing, aircraft operations, weight estimation, performance requirements, maneuvering, propulsion systems, environmental systems, and configuration layout. Issues that are marginally addressed in the course include environmental impact, economics, and airline requirements.

The design work is conducted in an interdisciplinary fashion, with design groups working as teams throughout the three-quarter sequence. The course culminates in a design review at the end of the year. The industry design review team includes engineers with expertise in aeronautics, manufacturing, propulsion, maintenance, structures, and control systems. The engineers come from companies and organizations including, but not limited to, Boeing, Lockheed Martin, Northrop Grumman, Rolls Royce, General Electric, United Airlines, and NASA. Our experience with the senior-level design curriculum has been that students gain valuable insight into the difficulties in designing an aircraft within the constraints of a group project and a deadline. Unfortunately, since the design course is their first in-depth team engineering experience, the students are typically not prepared to work in teams. In addition, the student's design skills are often inadequate, which shouldn't be surprising, since they had little or no opportunity to practice the art of design.

A variety of approaches to give students a design experience have been attempted at other universities, including teaming freshman with senior design students [7] and introducing students to engineering concepts in a unified set of courses in the sophomore year [8]. While we admired these approaches, we felt that we needed to develop a course that best tied in with Cal Poly's 'learn by doing' educational philosophy.

While we were seeing the need to increase student's design skills, pressures external to the university were also demanding improved graduation rates and student throughput. Most universities across the country were seeking ways to reduce the total number of units required for graduation, and our engineering curriculum was already at the maximum number of units allowed. Therefore, the over-riding restraint on any new approaches to design education was that the new material could not add any units to the existing curriculum. In addition, the curriculum changes had to provide an integrated approach to design from the freshman year through the senior year, with modules taking place throughout the student's academic career. We believed that these restraints were inviolable. A summary of the thought processes and efforts in creating the curriculum are reviewed in Ref. 9.

There were three main areas within the curriculum which were modified to better prepare the students for tackling design themes:

- the freshman engineering curriculum
- a sophomore introduction to design;
- teaching existing engineering analysis course from a multidisciplinary perspective.

Faculty included a team-teaching approach to segments of the curriculum where these issues were relevant. The goal was to integrate the multidisciplinary design approach throughout the curriculum from freshman engineering courses through masters-level design courses. This approach includes a new freshman engineering course, a new CAD/CAM modeling course, and a comprehensive approach to design in the senior design courses. These modifications also formed the basis for the creation of the sophomore design course.

THE SOPHOMORE DESIGN CURRICULUM

Given our desire to introduce students to design at the sophomore level, we faced the same dilemma that was mentioned earlier—the students don't 'know' enough to perform the design of an aircraft. Therefore, the first need in the course was to teach them engineering concepts 'just in time' and 'just enough', supplementing such teaching with computer tools that allow analysis to be performed at levels beyond the scope of the student's abilities. The second, less tangible, but equally important, need of the sophomore design course was for the faculty to mentor the students in design philosophy and engineering practice [10].

We outlined six primary goals of the sophomore design course (listed without order to importance):

- introduce students to aeronautical engineering fundamentals;
- introduce teamwork basics;
- introduce students to market/ethical/social considerations in design;
- introduce conceptual design philosophy;
- introduce presentation skills;
- immerse and mentor students in the design process.

The course we developed is two hours of lecture a week plus four hours of lab. The first five weeks of the course contain lectures that introduce students to basic aeronautical engineering nomenclature, fundamentals of flight, acceptable formats for homework and reports, classroom discipline, and how to use reference sources. Frequency of lectures decreases to an 'as-needed' basis for the last half of the quarter as students spend increasing time on their team assignment.

Team assignments are made at the end of the first week and the design opportunity for the quarter is introduced at that time. The focus changes from quarter to quarter and is chosen to reflect real-world needs and/or research interests. Examples are:

- Fall 1999: A light twin-engine general aviation aircraft. The aging fleet of general aviation aircraft offers new opportunities for modern designs.
- Spring 2000: A new aerial firefighter. The California Department of Forestry is currently (Spring 2001) seeking a replacement aircraft for their fleet of aging transports and bombers.
- Fall 2000: An Extreme Short Takeoff and landing (ESTOL) regional jet for the California Corridor. NASA/Ames Research Center's Powered Lift Project Office is conducting funded university-level research in this area involving Cal Poly faculty and students.
- Spring 2001: A Personal Air Vehicle. NASA/Langley Research Center is conducting funded university-level research in this area.

Over several quarters spanning two academic years, sophomores were given the opportunity to create conceptual designs of regional airliners to well-bounded sets of requirements established by instructors and by representatives from NASA/Ames Research Center's advanced concepts and powered lift office and Boeing/Long Beach's Phantom Works. Specific design requirements were:

- Sixty passengers with carryon baggage.
- One thousand statute mile stage length which could be interpreted as range.
- Three hundred knot minimum cruise speed at 25 000 feet.
- Meeting existing FAR Part 25 operator requirements.
- Takeoff and landing field length over 50 foot obstacle to be:
  - 1000 feet—Spring 2001
  - 5000 feet—Fall 2001
  - 3000 feet—Spring 2002
  - 2000 feet—Fall 2002
  - 4000 feet—Winter 2003
  - 2000 feet—Spring 2003 with 70 passengers and 1000 nautical mile range

Students in the sophomore design class present their work in a mini symposium during the final class day of the quarter to NASA and industry staff, as well as to interested department faculty and upper-division students.

The text used (*Introduction to Aeronautics: A Design Perspective* by Brandt *et al.* [11]) covers aeronautical engineering fundamentals and introduces the aircraft design process. A great deal of material covered during the design portion of the course comes from handouts prepared to be germane to the current design subject of interest. Handouts are similar to those given to seniors during the first quarter of Cal Poly's aircraft design sequence, but sophomores are not required to derive equations or do other than rudimentary parametric analyses.

The first team assignment of the quarter is to research aircraft that have been built in the past, or are currently in service, fulfilling the same mission or similar missions. Students then set performance requirements based on customer needs or on historical performance. Handouts take students step-by-step through specific conceptual design tasks beginning with initial weight sizing based on industry weight-fraction methods (an example method is published in Ref. 12, Chapter 5). The next related set of tasks has them create constraint plots based on descriptive equations for mission requirements (see Fig. 1). In the senior year design sequence, students are required to define these mission parameters and derive their own equations; in the sophomore design course, students are given general equations to describe mission profiles, but must decide which equations are pertinent (a reference handout is the Cherry and Croshere Constraint Method of 1947, Ref. 13).

At this point (approximately the second or third week of the quarter), students are ready to begin sketching configurations to meet their mission requirements and sizing efforts so far. The first task is for each student to sketch at least one configuration, then the teams discuss each and choose one or more to pursue. Additional handouts present pertinent specialty-related considerations (aerodynamics, thermodynamics, structures, weights, static stability and control) and analytical methods. Students are expected to divide the work among them, plan their time to accomplish required tasks, and work together and separately to bring their conceptual design to a point where it can be presented to industry and government representatives.

Unlike Cal Poly's senior aircraft and spacecraft design sequences which span an entire academic year, the sophomore design course is currently limited to one quarter, so students must be taught not only aeronautical engineering fundamentals but teamwork basics as well. As soon as class size stabilizes, students are divided into groups of five to eight, depending upon class size, with six being the preferred number. Classes meet for three hours twice a week with the first hour devoted to lecture and the remaining two devoted to related design work. Lectures cover introductory aerodynamics with an emphasis on aerodynamic theory and applications. Material covered the first four weeks will include discussions of standard atmospheric properties, definitions of lift, drag and moment coefficients for both airfoils and wings, Bernoulli's equations, the Equation of State, and the Momentum Equation. Students are drilled in reading standard airfoil charts and are then shown how to convert two-dimensional airfoil properties into three-dimensional wing properties.

Labs the first four weeks begin with team building exercises and an assignment to research existing and past regional airliners and compile a list of their performance, dimensions, weights, and (if possible) costs. A lab is then devoted to listing these aircraft on the board and then calculating basic descriptive ratios like lift-to-drag, transport efficiency (ML/D), takeoff thrust-to-weight ratio, takeoff wing loading, empty weight fraction, payload fraction, and fuel fraction. This visualization of airplane properties leads to discussions of similarities in airliner characteristics and to differences that might reflect market niches, state-of-the-art, and propulsion cycles. Students are then asked to create a curve fit for empty weight fraction versus takeoff gross weight as a prelude to initial weight estimates.

Once the design teams have a weight curve-fit, the classroom discussion shifts to using a standard

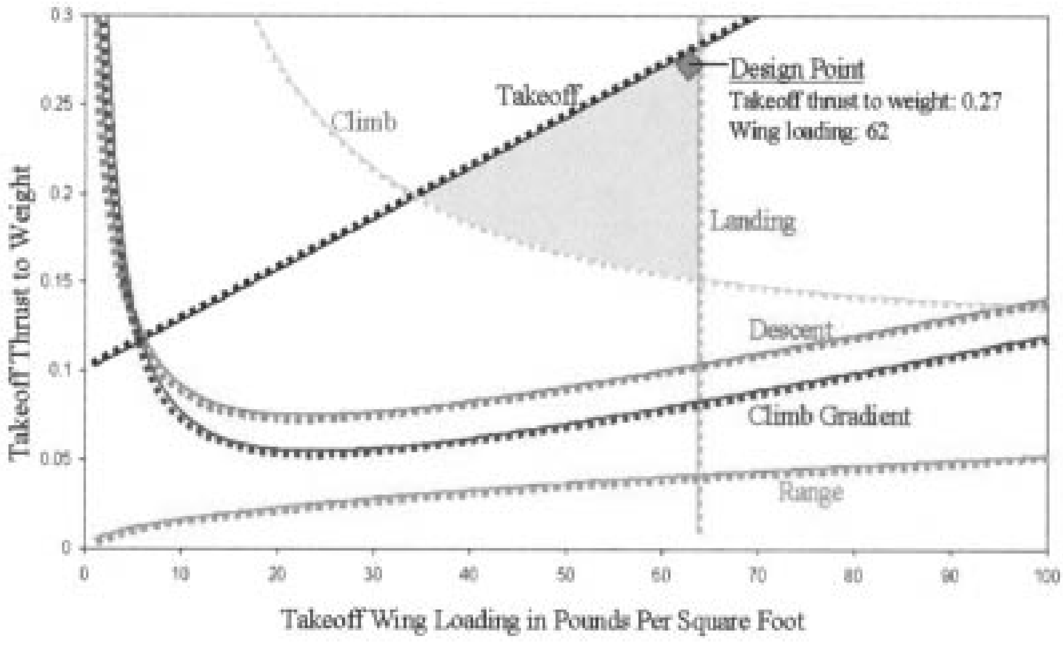

Fig. 1. Constrained design space for a regional airliner.

weight fraction method. The method used is similar to that found in Nicolai [12] to arrive at an iterated initial estimate of takeoff gross weight. While some students in each group create their first estimate of takeoff gross weight, the others begin creating a constraint plot similar to those found in Roskam [14] (see Fig. 1). For both these tasks, students are given performance equations to describe mission segments and FAR requirements [11].

Given an estimate of the design domain and takeoff gross weight, students can estimate both wing area and takeoff thrust. Pairs of students in each group will then research engine choices, wing aerodynamic properties required, and physical size requirements for the cabin and flight deck. During the next phase of work students are asked to individually create configurations which meet the physical constraints they've uncovered, then they down select configurations to one and begin exploring how the airplane might be built including how major subassemblies would tie together to distribute flight and landing loads. Ref. 15, for example, is a highly usable source of information for students during this portion of the design as a guide for airliner wing design, configuration layout considerations for airliners, nose gear collapse, nacelle clearance restrictions on tipover angle, etc.

Since student designs depend on good short takeoff and landing (STOL) performance, it is important that simple, but reasonably accurate, methods be used to estimate performance. For example, a simple relation for takeoff ground roll is given by [16]:

$$(s_{ground})_{takeoff} = \frac{\dfrac{13.08\dfrac{W}{S_{ref}}}{(C_{L_{\max}})_{power\text{-}off}}}{\left(\dfrac{V_{takeoff}}{V_{stall}}\right)^2\left(\dfrac{T}{W}-0.1\right)}$$

where:

W = takeoff gross weight in lbs
S_{ref} = reference wing planform area in ft^2
$(C_{L_{\max}})_{power\text{-}off}$ = takeoff wing $C_{L_{\max}}$
V_{stall} = stall speed corresponding to takeoff $C_{L_{\max}}$
$V_{takeoff}$ = liftoff speed in the same units as V_{stall}
T = takeoff thrust in lbs

A similarly simple landing distance equation may be used, such as [16]:

$$s_{landing} = \frac{118}{\sigma(C_{L_{\max}})_{blown}}\left(\frac{W}{S_{ref}}\right) + 400$$

where σ is the density ratio at the landing altitude.

In order to calculate takeoff ground roll (in feet), students must relate not only wing loading and thrust-to-weight ratio, but also 3-D wing performance. Getting the speed ratio requires a quick look at FAR Part 25. Arriving at a 3-D maximum lift coefficient requires choosing a 2-D airfoil, examining a variety of high lift devices, and incorporating their effects into the 3-D lift curve. Again, we supply an equation found in many STOL texts to add the effects of super-circulation and momentum direction changes to aerodynamic lift to estimate a total lift coefficient [16]:

$$C_L = (C_{L_\alpha})\alpha + 4.6\frac{S_{blown}}{S_{ref}} + \phi_{blowing}C_\mu \sin(\delta_{flap}+\alpha)$$

where

C_{L_α} = wing lift curve slope per radian
α = wing angle of attack in radians
$S_{blowing}$ = blown portion of the wing area
$\phi_{blowing}$ = blowing augmentation ratio
C_μ = momentum coefficient
δ_{flap} = flap deflection in radians

The momentum coefficient is defined in [17] as:

$$C_\mu \equiv \frac{\dot{m}_{blowing}V_{blowing}}{qS_{blown}}$$

Reference curves to quantify overall high lift system effects are also found in [18].

As students learn more about their designs they ask increasingly more detailed questions that reveal their realizations of how various aeronautical disciplines flow together to produce an integrated design. Students are encouraged to seek answers to their questions in the extensive reference library available in Cal Poly's aircraft design lab but there are many times when answers must come from impromptu lectures in what we've termed 'just-in-time teaching'. The lecture-style presentation is informal with one or two groups of students clustered around the ink board intensely interested in the immediate application of what they're learning to their design work. This is a labor-intensive way to teach technical material but it has proven crucial to the success of this approach.

Figures 1–5 show examples of student designs from the Spring 2002 version of the course.

Student teams were asked to design a commercial regional airliner with the following requirements (see a typical constraint diagram in Fig. 1):

- range of at least 1000 statute miles;
- 60 passengers;
- preferably a turbofan, but a turboprop was acceptable;
- take-off and landing runway length of less than 5000 ft;
- no cruise speed or cruise altitude was specified.

A great deal of design detail can be seen in Figs 2–4, which includes the three-view drawing of a candidate configuration (Fig. 2), the interior layout and weight and balance information (Fig. 3), as well as the internal layout of the wing (Fig. 4). Figure 5 shows a typical set of performance calculations for one of the regional airliners. A great deal of performance information is readily available to students

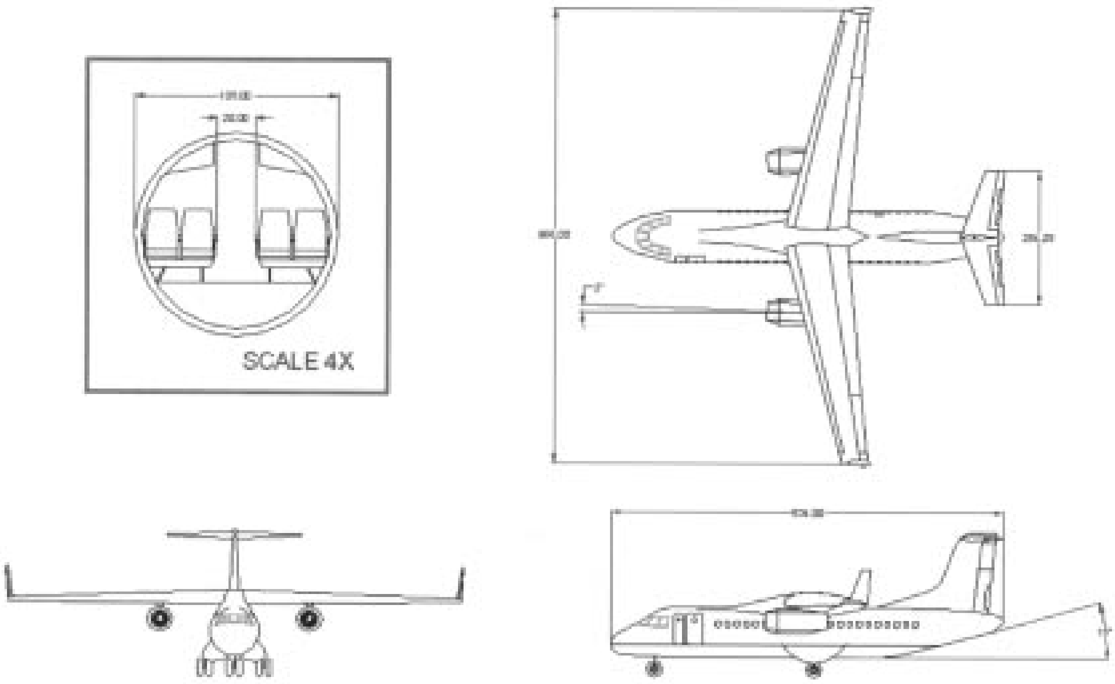

Fig. 2. Three-View Drawing for a STOL Regional Airliner.

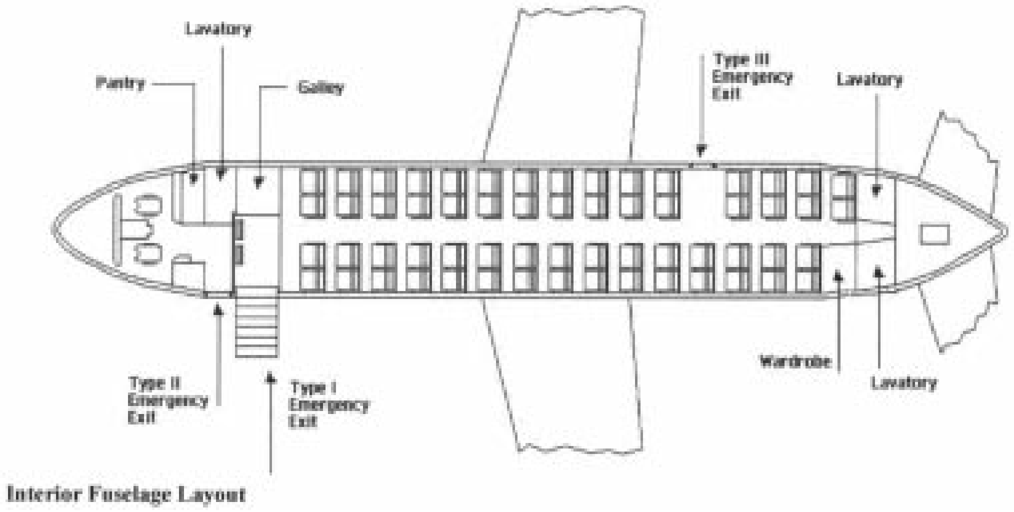

Fig. 3. Interior Layout and Weight and Balance Data for a STOL Regional Airliner.

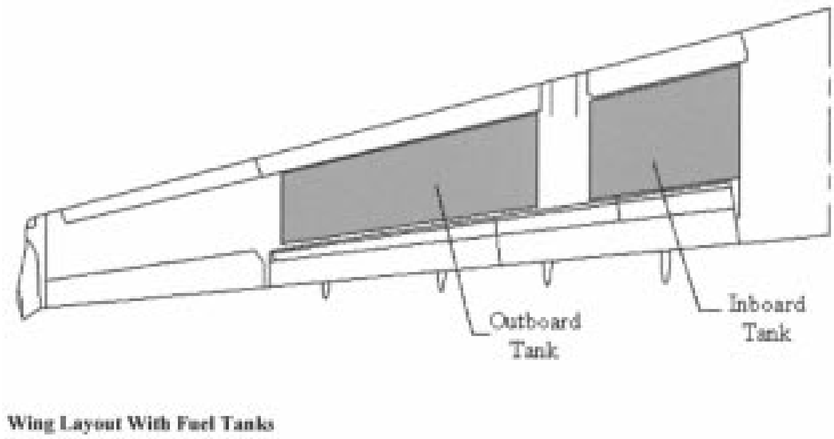

Fig. 4. Wing Layout for a STOL Regional Airliner.

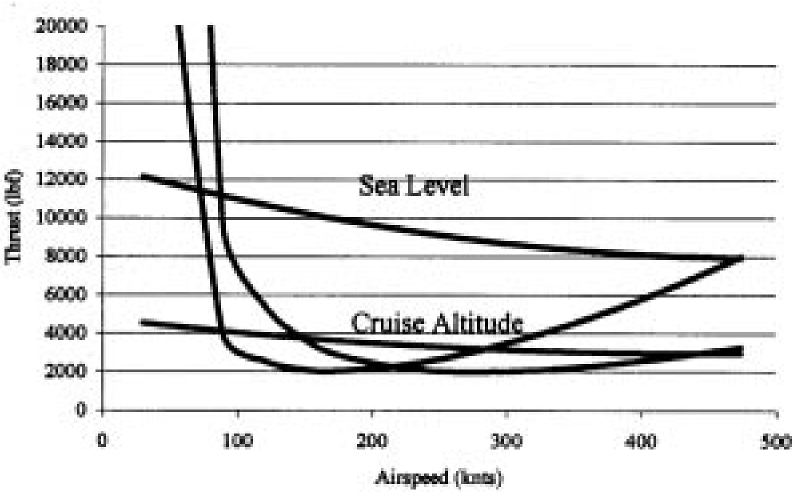

Fig. 5. Thrust Available and Thrust Required for a STOL Regional Airliner.

using the basic performance equations, which are easily programmed on spreadsheets. Performance parameters include, but are not limited to: range, endurance, ceilings, speeds, climb rates, and take-off/landing distances.

The students do dry runs of their final presentations prior to the mini-symposium and iterate on presentation materials and techniques. Each team turns in a comprehensive final report that describes their technical work, their teamwork, and allows them to reflect on the overall design and team processes. The report and presentation are required to address the following areas:

- purpose of the airplane;
- market—who will buy the plane?
- comparison of the airplane with at least two other competing airplanes (if they exist);
- all equations used in calculations;
- drawing of airplane (either using a CAD program or hand drafted);
- estimates of the following;
  - weight;
  - payload;
  - cost;
  - airfoil selection;
  - wing planform;
  - wing aerodynamics (lift and drag as a function of α);
  - L/D vs. speed;
- flaps;
- control surfaces;
- basic configuration and layout of the airplane, including the landing gear;
- cruise conditions;
- engine performance estimates;
- performance analysis at cruise altitude;
  - minimum and maximum velocity;
  - power (or thrust) required and power (or thrust) available;
  - rate of climb;
  - service and absolute ceilings;
  - range and/or endurance;
- spreadsheet showing performance calculations.

Students finish the quarter thankful that they are done with the work but at the same time thankful for the opportunity to present their designs to faculty and visitors who impart a real-world flavor to the course and stress the application of their design work to ongoing research. Companion papers discuss details of Cal Poly's sophomore aerospace vehicle design course ([19] and [20]) and one design project for a 3000-ft field length STOL regional airliner [21].

LESSONS LEARNED

While we have been very impressed with the designs completed by our students, our enthusiasm did lead to a problem of over-confidence. We kept asking the students to accomplish more each time the course was taught ('how much do you think they can do?'), and we also kept giving the students increasingly more difficult designs to accomplish. Finally, however, we asked too much! During Spring 2001 we asked the students to design a personal air vehicle, for which there are few existing designs. We noticed that the students struggled when the aircraft they were to design was outside the available historical data base and/or beyond the assumptions of the sizing equations (see, for example, what happens to typical sizing methods when the take-off distance decreases to zero!).

We concluded that the design should usually be equivalent to Boeing designing an aircraft like the 767–400 . . . take existing aircraft technology and improve or extend the design. Another option would be to ask the students to take existing aircraft technology and use it for an unusual purpose (such as a firefighting aircraft).

Students in the class also struggled greatly with the concept of constraint equations and design space. The earlier this concept is introduced and used the better! With a little explanation and some straight-forward examples the students quickly became familiar with the design constraints and begin to realize the limitations to their design (reality rears its ugly head!). This may be one of the most valuable lessons the students learn—there are very real constraints and difficulties in designing an aircraft, no matter how good they are at sketching fantastic aircraft designs. Tempering creativity with physical reality is one of the more difficult processes to overcome in engineering design. We believe that our students are well on their way to having a healthy balance of creativity and realism.

The course structure is very much dependent upon sophomores being far enough through basic courses such as physics, calculus, and statics that they can grasp applications to aeronautical engineering topics. By the first quarter of their sophomore year most Cal Poly students have reached this level. Therefore, we strongly enforce course prerequisites for this knowledge, even when students insist that they are ready to take the course. Students must also be given well-bounded and simple design projects which lend themselves to straightforward analytical description. Subsonic regional airliners are well-suited since there are many existing and past examples of successful regional designs and performance requirements are well-bounded by Federal Aviation Regulations.

A team-teaching approach works well, particularly when combined with a student teaching assistant in the lab. That gives students differing opinions and approaches to solving engineering problems which drive home the realization that there is often more than one acceptable answer to an engineering question. The teaching assistant also provides a barometer, or perhaps thermostat is a more accurate description, to how students respond to the increasing workload as the quarter progresses. These 'lessons learned' have led to a variety of modifications to the course as it continues to evolve and improve.

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CONCLUSIONS

A dilemma has faced engineering educators in recent years as accreditation and industry pressures have forced faculty to re-examine how and when they teach design. Traditional engineering programs viewed design as a poor step-child, often relegated to second-class status in research-dominated departments. In addition, design courses were seen as being purely an application of material that the students were taught in previous (or concurrent) courses. These views forced design to be one of the final courses taken by engineering students at many, if not most, universities.

An experiment in introducing the conceptual design of aircraft to sophomores has been undertaken to determine how much the students could accomplish without a great deal of prerequisite knowledge. Students were asked to perform a fairly detailed design of an aircraft in one quarter, including presenting the results as a final report and in a final presentation. While not all groups (or all students) achieve high levels of success in this endeavor, students were able to attain much higher levels of accomplishment than anyone had dared to dream. The benefit to the students is two fold (at the very least):

1. They have acquired a design (and team) mind-set while they are early in their academic careers, enabling them to see later coursework in a more coherent fashion.
2. The value of introductory coursework in the engineering curriculum (math, science, basic engineering science, as well as general education coursework) is now more clear to the students.

While we acknowledge that not all engineering disciplines will have the same level of success as we have had (luckily, many of our students come to Cal Poly with high levels of ability in flying and/or building aircraft), we believe there is more than a seed of success inherent in the sophomore design concept. We believe that such a program can breed excitement and enthusiasm in students, which will greatly help in retaining them through the difficult freshman/sophomore years, and lead to engineering graduates who will be looking forward to careers in the aerospace industry, regardless of whether or not they choose to be aircraft designers.

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