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STUDENT COMPETITIONS AS A FOCUS FOR AIRCRAFT DESIGN EDUCATION

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ABSTRACT

In May of 1992, a team of students from the University of British Columbia entered, for the first time, the SAE Aero Design (model airplane) Competition. They won first place in the competition against a field of 60 competitors from the U.S., Canada, and Europe. In 1993 a UBC team competed again, this time with a significantly improved entry. The team again finished first. This paper documents the team's experiences in these competitions, and emphasizes how the design of model airplanes for the competitions served the important didactic purpose of introducing aircraft design to the students.

INTRODUCTION

Student teams from the University of British Columbia (UBC) have entered the SAE Aero Design Competition twice, in 1992 and again in 1993. The teams won the competition both years, making UBC the first university to have fielded a winning team twice. The UBC experiences in the Aero Design Competition are related in this paper, and the suitability of the competition as a focus for aircraft design education is discussed.

The following section of this paper describes the Competition. Thereafter are sections that explain respectively the goals of aircraft design education, the UBC aircraft design process, and the merits and shortcomings of the competition as a focus for such an education. The paper closes with brief conclusions.

SAE AERO DESIGN COMPETITION

The SAE Aero Design Competition (commonly referred to as the "Heavy Lift" Competition) is an annual international model airplane competition, sponsored by the Engineering Society for Advancing Mobility Land Sea Air and Space (SAE). The competition was developed "to provide students with design experience and means (sic) of practical application of their engineering education [1]." The competition was first held in 1986, and has been held in different locations every year since then. In 1992, when it was hosted by Embry-Riddle University, 61 teams from across the United States, Canada, and Europe were involved in the competition. Wichita State University played host to the Competition in 1993. The number of competitors that year increased to 91.

The purpose of the Aero Design Competition is to design and construct a model airplane that can lift the largest payload subject to certain constraints. The principal constraints are: the planform area of all structures of the plane is limited to 1200 square inches ($0.773 m^2$); the plane must takeoff from, circle around, and land within, a 200 foot runway; the plane must accommodate a cargo box 5" × 6" × 10" ($12.7 cm \times 15.2 cm \times 25.4 cm$); and propulsion must be provided by a particular type of unmodified engine.

In addition to designing and constructing a model airplane, competitors must submit a lengthy technical report, complete with engineering drawings, that details their particular design (including a prediction of the maximum payload their plane can lift). They must also present an oral report about the design and compete in a flyoff. The teams are evaluated based on the quality of their written and oral reports, the amount of weight the plane can lift, and the accuracy of the payload prediction.

AIRCRAFT DESIGN EDUCATION

Before the Aero Design Competition can be discussed in the context of the training of aircraft designers, we must first address two questions. What is aircraft design? What are reasonable goals of aircraft design education?

Design has been defined as "an iterative decision making activity to produce the plans by which resources are converted, preferably optimally, into systems and devices to meet human needs [2]." Roskam [3] has narrowed this definition in the context of aircraft – "aircraft design is an iterative, non-unique process by which aircraft configurations, aircraft structures and aircraft systems are integrated and evolved such that the aircraft meets certain minimum standards in the following areas:

- mission performance, useful load and operational requirements
- airworthiness requirements, including structural durability requirements
- manufacturing and producibility requirements
- maintenance and accessibility requirements
- environmental requirements
- cost and profitability requirements."

The aircraft design process, it is generally agreed, consists of three phases [4,5]: a conceptual phase, a preliminary phase, and finally a detailed design phase. In the first, conceptual, phase the basic layout of the airplane is established. For example, the approximate fuselage length and diameter, a lifting surface configuration (canard, monoplane, flying wing, biplane, etc.), and a landing gear arrangement (tricycle, tail-wheel, etc.) would all be chosen in this phase. The preliminary design phase involves the selection of an airfoil section(s), the choice of the wing aspect ratio, the evaluation of the tail areas and tail volume coefficients, etc. Finally, detailed design involves taking the design to the point where engineering drawings of all parts in the aircraft can be made, i.e. finalizing the thickness of wing spars, the spacing of rivets on a rivetted skin, the layout of all the hydraulic lines, etc.

The single feature that distinguishes aircraft design from most forms of engineering work (and even from many different examples of engineering design) is the necessity to have a global view of what makes for good aircraft [6]. Knowing specific detailed information about the stresses in a wing spar, for example, may be very useful in the last phase of the design process, but is apt to cloud the picture during the first two design phases. If it is not possible to build a design team comprised solely of members who can think in terms of an aircraft 'system,' then it is at least necessary to have a smooth flow of information between all members of the design team, to ensure a global view is achieved.

If we accept these as appropriate defining attributes of aircraft design, we can consider what we should teach students. In view of the six aircraft design requirements listed by Roskam, it is clear that we must explain to students the concept of an operational mission and airworthiness (including structural durability), manufacturability and maintenance considerations, and environmental and cost factors.

These issues, however, are of only secondary concern. Because the concept of an aircraft system is central to aircraft design, one can forcefully argue that we must make students aware that a **successful airplane is a system of interconnected components**. No single part of the system is likely to be optimum, but the system as a whole is nearly so. Two related points about what students should know arise from this first remark:

1. When designing a complex system one commonly takes a **broad perspective to start, and refines the separate components of the system only as the design develops.**

2. Designing complex systems is normally iterative. One may develop a complete system, test it, identify its deficiencies, and re-design it. The iteration loop may only involve a single component of the overall system, too.

Because the design of any non-trivial aircraft will involve the skills of many designers, it is necessary to teach students the importance of **good communication** in a design group. Aircraft design is also highly complex, and hence students should be aware that **good planning and management** is necessary to develop a successful design (see also [7,8]).

Aircraft design training will likely have some additional benefits. By going through the process of designing an airplane, or at least a major subsystem thereof, students will perform stress, aerodynamics, and stability calculations, which can only serve to enhance their understanding of fundamental subjects. In addition, exposure to aircraft design will open students' eyes to the possibilities and interest of engineering design in general.

As a final note, it bears mention that one must be realistic about the amount one can hope to teach students about aircraft design. At the undergraduate level there is only a limited amount of time available (perhaps the equivalent of 2 or 3 courses) for aircraft design training – not enough for each student to go through an entire design (conceptual, preliminary, detailed) by herself, and certainly not enough to go through the design of a few different types of aircraft. To expect that, although a desirable goal, would be to expect to give the students more experience than most aircraft designers have after a decade.

UBC AIRCRAFT DESIGN EXPERIENCES

The Aero Design Competition 'arrived' at UBC in the summer of 1991. An undergraduate summer student spoke with the author and another faculty member about mentoring a team. Shortly after the beginning of term a group of interested students was interviewed and a complete team fielded. Very little further will be said about the activities of that year, other than to remark that in retrospect the efforts of that first year were largely misguided. Almost half of the academic year was spent pursuing three different aircraft designs (a flying wing, a canard, and a conventional monoplane) all the way from the conceptual design phase through to the detailed design phase. Only in December was the obvious finally recognized – the team had neither the manpower nor the time to proceed with all three designs. By virtue of great and extended effort, and good fortune, the UBC team ultimately lifted the most weight – and won the competition – that year. Of greater importance, though, was the knowledge gained about how to mentor an effective Competition team. This hard-earned knowledge is summarized below.

The significant first step in putting together a team for the Competition is to recruit a team leader. The purposes of the team leader are to motivate the other team members, primarily by good example, and to be the principal organizer. The team leader serves approximately the same role as the upper level manager at large aircraft firms, who oversees the technical development of a new airplane. Much the same purpose is served by the faculty advisors, who are technical resources for the students, who motivate the students when necessary, and who provide continuity from year-to-year.

The team leader then selects a group of team members who are committed to devoting much time and imagination to the development of a new model airplane. This step is particularly important because, without sufficiently motivated and intelligent students, it is difficult to foster the teamwork that is essential to a successful competition entry. The team leader, members, and faculty advisors, comprise the UBC equivalent of the Skunkworks.

Once the team members are selected, the team is divided into small groups, each of which is responsible for a particular aspect of the airplane design. One group is responsible for the plane propulsion system, another for the aerodynamics, a third for the structural design, and a fourth for the empennage design and stability calculations. Due to the special nature of this competition, one team member is responsible for keeping track of the overall planform area and the aircraft structural weight. The team captain arranges weekly meetings. The purpose of these meetings is to motivate team members, and to ensure there is good communication and camaraderie among the team members.

An important factor in UBC's success has been the timetabling of the plane's development and production. Work on the competition was begun early, and was organized such that each team was able to take an iterative approach to aircraft design and construction. Virtually every component of the airplane was designed, tested (both structurally in testing machines, and aerodynamically in a wind tunnel), and redesigned. For example, the landing gear was designed, built, and redesigned and rebuilt three times. This testing was not limited to individual aircraft components; a rigorous test flight program was also run each year. The iterative design process was not limited to a single year. The 1993 design was sufficiently similar to the 1992 design that the knowledge gained from the 1992 competition was built on in 1993.

The last paragraphs have been devoted to an explanation of the organizational structure of the team, in order to emphasize that good communication, teamwork, and appropriate timetabling are central to a successful Competition entry. Some of the technical details of the aircraft model design are discussed below. The complexity of these details suggests, correctly, that the team received significant technical support.

The requirement in the Competition rules that the model takeoff from a 200 foot runway is in many regards the most important rule in the competition. One can show, using a simple takeoff analysis, that this rule limits successful competitors to designing STOL (short takeoff and landing) aircraft. The analysis also reveals that the design emphasis for competition aircraft is different from that for conventional aircraft. For example, because the model spends very little time in cruise conditions (the competition is basically won or lost in just getting the aircraft to rise off the runway within the alotted distance), aircraft drag is only of secondary importance. Similarly, the maximum lift coefficient of the airplane is of much greater importance than its lift:drag ratio. The takeoff analysis narrowed our focus to four aspects of the airplane design – the wing airfoil section, the aircraft structural weight, the landing gear rolling resistance, and the propeller selection. Of course, other aspects of conventional aircraft design, such as structural strength and stability, were also of concern to the team.

Lifting surface configuration selection was the first step in the conceptual design of the aircraft. A "flying wing" configuration for the airplane was considered when UBC first entered the Competition, on the grounds that all 1200 square inches of a flying wing model generates lift. After some study, this configuration was recognized to be unsuitable because the stability of such a plane is achieved only by having an airfoil geometry with poor lifting characteristics. The canard configuration was also considered in 1992. Unlike a conventional monoplane, in which downforce is applied on the tail to balance the negative pitching moment of the wing, both the canard and the wing generate an upwards force (and hence more total lift). On the basis of some stability calculations, the canard configuration was also discovered to be a non-viable option. The team was thus (fortuitously, in terms of practical design experience for the students) left with the task of designing a high performance conventional monoplane.

Monoplane aircraft can be of a high wing, mid wing, or low wing design. A high wing configuration was selected for all the Competition aircraft for two reasons. A high wing has greater wing tip clearance than the other designs (and hence less chance of a disastrous wing clipping on takeoff or landing), and it is also less subject to ground effect (which can make the other designs "float" on landing). Not surprisingly, a high wing design is also the most popular geometry for STOL aircraft.

A conventional tail geometry was selected for all Competition aircraft both for its simplicity and because during stall the elevator is safely below the wing wake. The tail size was chosen to yield tail volume coefficients close to that of conventional airplanes (i.e. around 0.4 and 0.2 for horizontal and vertical tailplanes, respectively).

Because the competition rules require that the fuselage accommodate a box of specified size, the fuselage size and shape was largely pre-determined. This prespecification is not characteristic of conventional aircraft design.

As explained above, developing an airplane with a high maximum lift coefficient is central to success in the Competition. In 1992 the best "off-the-shelf" airfoil section was selected (the Eppler 423, with a $(c_L)_{\max} = 1.9$). In 1993, following some analysis and extensive wind tunnel testing, a new airfoil section, the JF1, was developed. This section has a remarkably high $(c_L)_{\max} = 2.3$. Finally, after still further analysis and wind tunnel testing, we have this year identified a single element airfoil section with a maximum lift coefficient greater than any we have ever seen reported.

A great deal of thought has also been put into good, lightweight, construction methods. In 1992 UBC opted for a balsa wood model with fibreglass and carbon fibre reinforcement (Figure 1). The result was a model of adequate strength (tested up to a 2g loading) that was also one of the lightest competition entries, at about 3.4kg. For the 1993 entry (Figure 2) we believed we could improve substantially on this weight, and simultaneously increase the strength of the plane. The airplane structure changed from being primarily balsa wood to being primarily foam and fibreglass, with other composites used for structural reinforcement at key locations (e.g. carbon fibres were used in the wing spar). As a result of these improvements, not only was the airplane mass reduced, but the wing strength was also increased; the 1993 model was tested up to a 4g loading.

One of the structural features of the airplane that underwent a most effective and elegant redesign was the landing gear. The 1992 version of the airplane had a very stiff, heavy landing gear, with high rolling resistance. The following year it was realized that a shock-absorbing landing gear would reduce the impulse loading on other parts of the airplane structure, and therefore would be beneficial. One team member devoted a good fraction of a year experimenting with different materials and landing gear configurations, before finding one with the combined properties of light weight, great structural strength (able to withstand a 4g load), good shock absorption, and low rolling resistance.

Development of improved thrust sources has also been a factor in our success at the Competition. In 1993 careful wind tunnel tests were run on a number of stock propellers. The thrust generated by the engine/propeller combination was thus increased by 10% over the 1992 performance. This year the students are attempting to develop their own propeller for the Competition. They have combined Blade Element Theory with a two-dimensional computational aerodynamics program to generate a propeller shape with optimum thrust characteristics. The propeller shape generated in this way has been sent to a Numerically Controlled

Milling Machine. The machined propeller is expected to produce 10% more thrust than the 1993 version.

In summary, the success of UBC in the competition is attributable to a few factors – a good organizational structure with effective communication between the design groups, an iterative approach to aircraft design, concerted effort by all participants, and strong technical support.

MERITS AND LIMITATIONS OF MODEL AIRPLANE COMPETITIONS AS A FOCUS FOR AIRCRAFT DESIGN EDUCATION

Following on the earlier discussion of the purposes of aircraft design education and the experiences of the UBC Aero Design Competition teams, the effectiveness of the Competition for aircraft design education can now be discussed.

One of the principal didactic benefits of the Competition is that students work in teams. Team leaders become experienced, if not necessarily good, leaders. Other team members learn how to cooperate on a big project. The effective communication of information is also learned during the course of the year, and is emphasized during preparation of the written and oral reports. Finally, the students are at least made aware of the need for a comprehensive timetable for a large project, even if they are never entirely successful in generating such a timetable.

Students involved in the Competition also learn a great deal of technical information. The students involved in wing geometry selection, for example, learned about aerodynamics. One could argue that the lessons they learned were not entirely useful, because they designed an airfoil for a highly unusual plane (at low Reynolds number, and for which the lift:drag ratio is unimportant). Thus, for example, the airfoil sizing/geometry selection procedure of Raymer [4] could not be used. On the other hand, team members did run a computational aerodynamics program, perform wind tunnel tests (with all the academic benefits of such testing [9]), look at stall characteristics, calculate lift coefficients, and do a myriad of other technical activities that have enhanced their understanding of aerodynamics. Similarly, the group involved in the aircraft structural design learned important lessons about structural load testing, composites, stress concentrations, and manufacturability (see also the discussion by Palmer and Sherwin [10]), although nothing about construction techniques using the most common airplane material – aluminum. Different team members performed stability, propulsion, and electronics analysis and testing. All groups had the salient engineering experience of performing a back-of-the-envelope calculation in order to get a sense of the physics of a problem.

The students also had the experience of building and repeatedly flying (and rebuilding as necessary) their aircraft, which emphasized the importance of manufacturability and durability in aircraft design.

As a result of the division of labour between a few different team groups, no individual team member had direct experience with all technical aspects of the aircraft design. Good communication between team members at the meetings should ensure that each student has at least a sense of the activities of all the groups involved in the design; technical details that students don't learn directly are picked up in part by osmosis.

The Competition is therefore both a very effective vehicle for educating students about the organizational aspects of aircraft design, and a reasonably effective one for educating students about some of the technical details of design. However, there are some key aspects of real aircraft design for which the Competition gives them no training.

The Competition aircraft are not designed for commercial use. Hence, they have not been designed to comply with FAA airworthiness regulations, which often guide the design process of real aircraft [11]. Such real-world considerations as the ability of commercial jets to climb with an inoperative engine, to have adequate fuel reserves at the end of a mission, and to fly stably even with the loss of an engine, were all ignored in the airplane design because **safety** is not an issue in the Competition. Furthermore, there is no consideration given to the **environmental impact** of the airplane (both in terms of engine emissions and noise production). Ease of **maintenance**, an important requirement in the design of real airplanes, is not considered during the Competition design process. Although the team must produce a plane within a limited budget that they control, **economics**, a consideration that is very important in airplane design, is virtually a non-concern.

In brief summary, participants in a Competition team have been exposed to many technical issues, and group communication concerns, that are at the heart of aircraft design. An understanding of other important aspects of aircraft design, such as airworthiness, maintenance, and economics, is not conveyed to the students.

CONCLUSIONS

Students who have been involved in the SAE Aero Design Competition teams at UBC have learned many lessons about aircraft design. Not only was their knowledge of aerodynamics and aircraft structures gained in traditional courses reinforced, but in addition they gained valuable experience working in a team, doing an iterative design, doing flight and other testing, and working on the design of a complete airplane rather than merely on its individual components.

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Fig. 1 The 1992 UBC competition airplane.

Fig. 2 The 1993 UBC competition airplane.