A BRAZILIAN EXPERIENCE IN TEACHING AIRCRAFT DESIGN

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Abstract

The methodology for teaching Aircraft Design at the Center for Aeronautics Studies of the Federal University of Minas Gerais is presented. The design phases are commented pointing out the step-by-step procedures. Teaching techniques to achieve the best performance are also described. Three recent student projects developed on the Aircraft Design course are presented in order to demonstrate the methodology highlights. These results show the design quality achieved in terms of solutions and detailing. Feedback from the students and from the industry confirms the suitability of the described methodology to the modern Brazilian Aeronautical Industry, which has demonstrated undisputed leadership on the international aircraft market.

1. Introduction

Brazil has three major universities that teach aeronautical engineering. The oldest one, created by the Aeronautical Ministry of State, is the Aeronautical Technological Institute (ITA) founded in the fifties. During the sixties, the Federal University of Minas Gerais (UFMG) created an Center for Aeronautics Studies (CEA) that supports, to this day, the Aeronautical Engineering undergraduate course of this university. This course, along with ITA and the recently created course at the University of São Paulo at São Carlos (USP-SC) city, is responsible for the education of the majority of the professionals in Aeronautical Engineering in the Brazilian aeronautical industry.

At CEA-UFMG, Aeronautical Engineering is a major within the mechanical engineering course. Throughout the last two years of their course, students have lectures in specific courses in Aeronautical Engineering. This university believes that this academic arrangement is first-rate for schooling, in particular due to its multidisciplinary approach. The specific classes in Aeronautical Engineering cover subjects on aerodynamics, stability and control, performance, structures, maintenance, construction, and design (CEA,2006).

In regards to the airplane design course in particular, CEA-UFMG has peculiar aspects in didactics which are the main focus of this paper. The philosophy behind the class is characterized by the opportunities given to students to be near practical applications in engineering. As Prof. Fielding and Prof. Jones of Cranfield University describe in their paper "Graduate-level design education, based on flight demonstrator projects" (Fielding and Jones, 2000), CEA-UFMG also believes that the best way of teaching design is allow the students a "hands on" education or, in other words, learning by doing. The modern designers need not only to be aware of all the intermediate stages between concept design and certification, but also to be experienced in them. They also have to be familiar to team work, since design teams are the currently way that the industry works.

Through the Aircraft Design class, students participate in the design of a complete aircraft, covering phases related to conceptual design, preliminary design and small tasks in detailed design. Throughout the history of this course, several different didactic approaches were adopted regarding the way students usually work on the design of an aircraft, i.e., team or individual work and specified or non-specified design requirements. Independently of the didactic approach, ultimately students must begin an aircraft development using simple methods and tools (including comparative methods and hand-made drawings) and, gradually, throughout the design process, escalate into the use of more sophisticated techniques, including Computer Fluid Dynamics tools, three-dimensional Computer Aided Design software and wind tunnel tests.

The goal of this work is to give a short presentation of the projects developed by these students during the past years, including discussions on the methods adopted, main difficulties, results and perspectives. A detailed discussion is also presented on the efficiency of adopted methods, especially regarding the Brazilian context.

2. The organization of the Aeronautical Engineering course

As mentioned before, the undergraduate course in Aeronautical Engineering of UFMG is formatted as a major within the Mechanical Engineering course. Currently, the total curriculum credit load is around 1,200 credits (corresponding to 3,600 hours), divided through the 5-year period of the course. From this credit load, 220 credits (660 hours) are dedicated to specific core courses from the aeronautical area. The core courses currently offered are:

- Introduction to Aeronautical Technology
- Aerodynamics
- Stability and Control of Aircrafts
- Aircraft Performance
- Theory of Aircraft Structures I
- Theory of Aircraft Structures II
- Aircraft Maintenance and Repair
- Aircraft Systems
- Aircraft Design I
- Aircraft Design II

Evidently, other disciplines of the Mechanical Engineering course complement the student required knowledge in the Aeronautical Engineering field, such as Fluid Mechanics, Strength of Materials, Thermodynamics, Fatigue and Fracture, among others.

Also, there are optional disciplines offered to complement the student education, such as Aircraft Flight Testing, Acoustics, Turbulent Flow, Engineering Optimization, Calculus of Variations, Theory of Composite Laminated Plates, among others.

3. The Aircraft Design course

The Aircraft Design course is ministered during the two last semesters, when the students have already acquired most of the required knowledge to become Aeronautical Engineers. Therefore, in this course, the students have the opportunity to apply and test all the material learned so far, specifically in a complete aircraft design. In this process, theoretical classes are presented in order to expose different design philosophies and techniques, including system integration and computer aided design (CAD) and engineering (CAE). Commercial codes are available to the students so that they can familiarize to the current tools. On the top of that, a complete aircraft design is required as a class report, giving to the student the opportunity to exercise their abilities of decision making and incorporate creative engineering solutions.

In order to implement this discipline, one has to keep in mind that it is very important to give a broad view of the design product (aircrafts, in this particular case) to the Aeronautical Engineering graduate. It is known, from feedback given by senior Aeronautical Engineers from EMBRAER (Brazilian Aircraft Company), that the success of a professional into a competitive work market, specifically for product development, is directly linked to his/her capacity to treat problems as a whole and not as a detail. In other words, a broader view gives a better capacity of problem solving than a narrower one. Therefore, it has been a priority for the University a course formatting that allows the student a broader view of the tasks, problems and solving methods in the development of aircrafts.

Different work models have been adopted in order to apply this view in teaching Aircraft Design in the UFMG. Student work teams and individual design approach were experimented. Nowadays, the task of teaching this discipline has reached a particular format that agrees with the philosophy of broader view described in the previous paragraph.

Work teams

There are two basic possibilities to form work teams in the Aircraft Design course: (i) individual or (ii) collective.

The advantage of developing the course with individual student work is to make sure that all students will execute the different types of tasks assigned to them in the process of aircraft development. However, due to the limited time for expositive classes and elevated extra-class work load the aircraft design could not be very detailed. This was the course formatting at UFMG up to the end of the 90's. The developed aircraft, thus, were generally light aircraft, with one or two occupants and with reciprocating engine and propeller propulsion system. In some cases, sailplanes were designed, but the necessity of including an reciprocating engine and propeller propulsion system into the design led to the discouragement of this kind of aircraft. Several aircraft developed on this course with this approach became later real products, such as the ultra light aircraft AD-01 Pégasus and the speed aircraft CEA-308 (CEA,2006).

Currently, it has been adopted the collective work team approach, including 5 to 7 students to develop the overall project. This allows the development of more complex projects and, therefore, with a higher level of information to be managed and developed. Unfortunately, in this formatting model it is not possible to be sure that all the students have the same dedication and learning during the process of teaching the course. However, the only variable that influences the student dedication in this case is his/her personal will to overcome the difficulties faced into the collective work. This makes this formatting to be more similar to the work environment where it is required to engineers to be capable of team work. Special attention is required to the task of evaluation the students' work, which tends to be different in this case. This will be discussed later.

Design type and task assignment

When using the individual work approach, it was almost impossible to define a particular design specification to be followed by each student due to the large number of students attending the course.

Therefore, limits were imposed in order to allow, at the same time, a minimum quantity of topics to be covered by the student in his/her formation with a maximum level of design detail that was feasible to be achieved in the time frame.

Once the course is taught through work teams with several students, it has been required the design of an aircraft specification for each team. This approach leads to more complex and detailed aircraft specification and is more adequate to the work force of the team, resembling the real work environment of the aircraft industry. However, due to the high quantity of information to be managed during an academic two-semester year, some precautions should be taken while using this approach.

First, it is important to keep in mind the path that the student should follow in order to create the requirements to induce this path in the design specifications. For instance, if an UAV (Unmanned Aerial Vehicle) is specified with emphasis in the aircraft control, the students may not dedicate to other important aspects such as aerodynamics, structures or design and manufacturing details, and give more attention to simulation and control. Therefore, the broader multi-disciplinary view of the design is lost in detriment of a narrower specialized view. It is preferred to give to the student a narrow design specification, in order to give him/her the impression of realism in the design development, but the design specification should also be broad enough to allow the student to cover all the important design areas, also giving a broader generalist view of the problem.

Another important aspect into the design development is the task division. This aspect has a direct impact on the degree of specificity required. One option is to induce individual members of the work teams to advance into the preliminary design individually, and later select a particular aircraft to be detailed. The problem in this option is obvious: everyone would like to detail their own aircraft. Therefore, it has been preferred to select a project and perform the preliminary and the detailed design within the work team.

Chronogram

Due to the enormous quantity of tasks to be executed and managed, the definition of a detailed chronogram to develop these tasks is fundamental. This chronogram has been defined by the instructor of the course and it is delivered as a design constraint. This approach is more convenient to the development of the course, mainly to prevent delay in the deliver of the tasks by the work teams and to allow the instructor to follow the tasks developed by the teams.

Design methodology

The design methodology adopted in the Aircraft Design course is not restricted to the methodologies currently found in the literature (Roskan, 1997, Raymer, 1992, Torenbeek, 1976, Kroo and Shevell, 2001). On the other hand, aspects and procedures of the modern authors are mixed and classified in order to take advantage of the highlights offered by each one of them.

Great part of this methodology compilation was developed by Professor Cláudio Pinto de Barros, founder of the Aeronautics Engineering in UFMG and creator of the discipline of Aircraft Design (Barros, 2001). In his work, Professor Barros mixed different design procedures and techniques proposed by other authors, and added others developed by his own experiences in light aircraft design at UFMG, which are presented later in this paper. This resulted in a methodology adapted to the Brazilian reality, presenting adequate didactic aspects to be used in an Aircraft Design course.

In general, this methodology does not differ from the other proposed by modern authors, but its presentation and references facilitate the development of light subsonic aircraft. This kind of aircraft is generally the most adapted for teaching aircraft design to students due to its moderate quantity of details. Therefore, this methodology has been chosen to be used in the Aircraft Design course at UFMG among the other methodologies found in the literature.

Design phases

The first step in conceptual design phase is the definition of a list of priorities and the development of comparative methods. The importance of a list of priorities is presented to the student, so that decisions taken during the design development are not contradictory. In reality, the definition of this list of priorities in each work team is a form of introduce the particular view of their members into the design development. Therefore, even for the same design specification, different work teams will have different priority lists. As for the comparative methods, their execution has been important for different aspects, among them:

- introduction of aeronautical culture in the student, keeping in mind that most do not know the market environment, past and present, in which the product will be developed;
- introduction of a notion of the order of the quantities used in the design, not only for physical characteristics (size and weight), but also for performance characteristics (speed, endurance and range).

Important information is that the comparative methods should not be used to define average values for a particular design, but to perceive important parameters to develop a better design instead.

Following the first step, the student will face the weight estimation for the aircraft. In this step, the methodology proposed by Roskan (Roskan, 1997) is used. Simultaneously, graphs of wing load versus power weight ratio are studied to serve as a basis to define the preliminary aircraft dimensions.

In both first and second steps, it is observed that the students have great difficulty in manage parameters to be estimated and parameters available for calculation. For the parameters to be estimated, the observed difficulty is natural since engineering students basic formation is related to calculating and dimensioning rather than to designing. Therefore, it is important to help students in this process of parameter estimation, showing how their insights influence the overall design development.

Other difficulties are observed when it is required the use of the previously acquired knowledge in other disciplines to help in this parameter estimation procedure. For instance, it is trivial for the students to use the equations of Breguet to estimate the fuel consumption for range and endurance regimes, but the definition of the glide ratio in this estimation, according to the design specification and to the typical aircraft missions, is not a simple task for them.

Therefore, particularly in these two first steps, expositive classes are required not only to remind the students the basic concepts that could be useful, but also to demonstrate their application. When the students have initiated their estimate calculations, it is important to evaluate their performance within the class time, criticizing and suggesting modifications, so that the whole class can observe the development of all teams and thus increase the individual capacity of criticism on the tasks developed.

The subsequent steps involve the definition of the external configuration, internal configuration, primary manufacturing processes, and materials to be used. In these steps it has been important to coordinate detailed discussions with the students with respect to the decision making, mainly concerning the technical feasibility of the selected solutions.

The end of the conceptual design phase allows the initiation of the first drafts of the aircraft, starting the preliminary design phase. It is required to the students to make these first drawings by hand, without using drawing tools as suggested by Young (2000). Evidently the results are not motivating, but they are important to give the students a complete perception of the creative process. It is also required to the students to bring slides of their first drawings to be projected in class, so that the instructor can make a sequence of suggestions and modifications on the drafts. These interventions are not available to the students after class since they are spontaneous and unpredicted. This obligates the students to absorb the introduced ideas and to create their own improved solutions to be presented in the next class.

Simultaneously to the creative process of the aircraft configuration (three-view drawing), there are some other aspects presented such as wing and stabilizer aerodynamic profile selection, manufacturing and assembling details, and preliminary system development (landing gear, control, structural configuration, etc.).

The first semester is finalized with the students performing detailed weight estimation, preliminary drag polar estimation, and drawing evolution, starting from hand drawings, two-dimensional CAD drawings, and, finally, three-dimensional CAD modeling using the software SolidWorks.

The second semester is dedicated to continue the design process, finalizing the preliminary design and executing the first cycle of the detailed design. In this semester, most of the classes are expositive and the students are required to initiate the detailing of the internal components of the aircraft based on the tree-dimensional drawing developed on the first semester. This detailing includes: (i) definition of the morphology of the structural components; (ii) installation of the propulsion system; (iii) definition of the control mechanisms; and (iv) installation of the general systems (fuel, electric, hydraulics, air-conditioning; etc.). It should be noted that this detailing includes the structural calculation of the wing, empennages, and fuselage. On the top of that, it is also required to students the execution of detailed analyses of: (i) aerodynamics; (ii) longitudinal and directional stability and control; (iii) performance; and (iv) loads. At this point the student must have completed all the courses related to these topics. Therefore, the execution of these calculations is nothing more than the repetition of procedures learned in the specific disciplines previously attended by the students.

The dynamics of the classes in this semester is then based on the presentation of detailed three-dimensional drawings during the classes. Multi-media equipments are used to project the detailed drawings of each team, which are subsequently commented and discussed.

4. Examples of aircraft design

Speed Aircraft – CEA-308

The aircraft CEA-308 was designed in the Aircraft Design course during the year of 1999.(Iscold, 1999) It is important to observe that tools of three-dimensional computational design were not available at that time. Therefore, the phases previously described that included three-dimensional drawings were executed using only two-dimensional drawings.

The design specification was simply to develop an aircraft to obtain the speed world record within a three-kilometer circuit in the category FAI C1-a0 of the International Aeronautical Federation.

A sequence of conceptual studies was initiated in order to design the best external configuration in order to achieve the design specification.

These conceptual studies converged to the execution of a conventional aircraft, which could be at the same time efficient and simple to detail and calculate.

Several references related to the design of speed aircrafts were used to perform the preliminary design, among them the experiences of Bruce Charmichael (Charmichael, 1993), and the details suggested by Michael Arnold in his project AR-5 (Arnold, 1997). Since there was not a wind tunnel available at that time to allow a more detailed study of the aerodynamic configuration of this aircraft, the design was based on these references and later confirmed by computer simulations.

The selection of the materials and the manufacturing processes were performed based on the possibility of construction of a prototype of this aircraft, using student work force. Therefore, moldless lamination of composite glass-fiber/epoxy sandwich with styrofoam core was selected to facilitate the construction, following recommendations of Burt Rutan in his projects Vari-Eze e Long-Eze.

The detailed calculations were particularly dedicated to the aerodynamic simulations, using a drag-buildup procedure. This methodology is more adapted to the determination of the aerodynamic characteristics of aircrafts in flight and includes several semi-empirical procedures to evaluate non-conventional drag, such as landing gear details, propeller, and air inducing engine system.

The manufacturing of a prototype of this aircraft was initiated by the undergraduate and postgraduate students of CEA-UFMG in the beginning of the year 2000. By the beginning of the year 2002, the prototype made its first flight. The flight test program was performed until September of 2002, when it was decided to ground the prototype to exchange the engine in order to increase the aircraft speed. On the flight test program, it was observed that even without a adequate preparation to achieve high speed (high pitch propeller and finishing refinement), the aircraft showed excellent aerodynamic characteristics, reaching the speed of 260km/h. Currently this aircraft is in the final phase of preparation for a new flight test program after the improvements.

Basic instruction aircraft – Brati

The aircraft Brati was designed during the year of 2005 attending to the specification of a basic instruction aircraft which could be configured, during its manufacturing, either as a nose-gear or as a tail-wheel aircraft and as a VFR or as a IFR. The detailed design specification was:

- certification: FAR-PART-23/CS-VLA;
- maximum leveled speed: between 200km/h and 300km/h;
- maximum range at 10,000ft: higher than 800km;

- basic equipments: VFR, IFR (optional), ELT, VHF radio, transponder, navigation lights, headlights, ballistic parachute;
- characteristics: nose-gear or tail-wheel versions, low fuel consumption, high flight quality, nice aesthetics, high safety (passive and active) level.

The weight iterative estimation process, in the first step evaluation resulted in an empty weight of approximately 4,700N. This value was coherent to the results from the comparative methods. The wing load ratio was estimated as 570N/m^2 and the weight power ratio as 83.8N/kW.

An interesting development to be presented is the evolution of the aircraft sketches and drawings. Figure 3 shows a chronological evolution of the drawings, from the first sketch hand made in the class room, to the last aircraft drawing, executed using a CAD software.

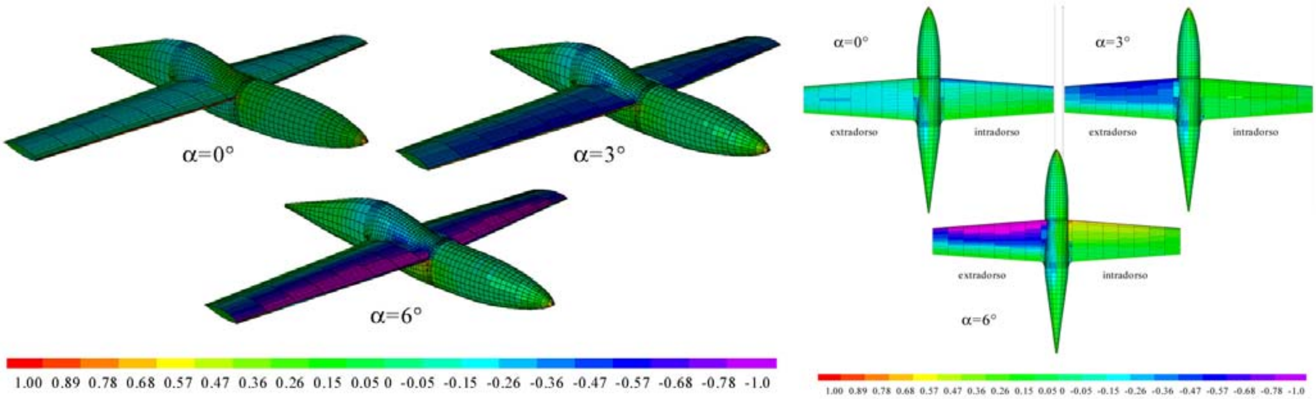

Figure 1 – Examples of aerodynamic analysis of the aircraft CEA-308 (pressure coefficient)

Figure 2 – Prototype of the aircraft CEA-308 in construction and in operation

Figure 4 presents a final view of the three-dimensional CAD drawing including the details developed during the course work. Figure 5 presents the degree of detailing achieved, showing the solution developed for assembling the nose-gear or tail-wheel configurations. Figure 6 depicts some examples of technical drawings for manufacture. It can be observed the high level of detailing, showing that the students can execute broader designs and experiment advanced phases of detailed design.

The success of the design could be measured through the verification of the design specifications achieved. A grade could be easily assigned to this topic as well as to the organization and the coherence of the final project. The final report can be seen at the site: http://www.demec.ufmg.br/Cea/Projetos/2005-BRATI01.pdf

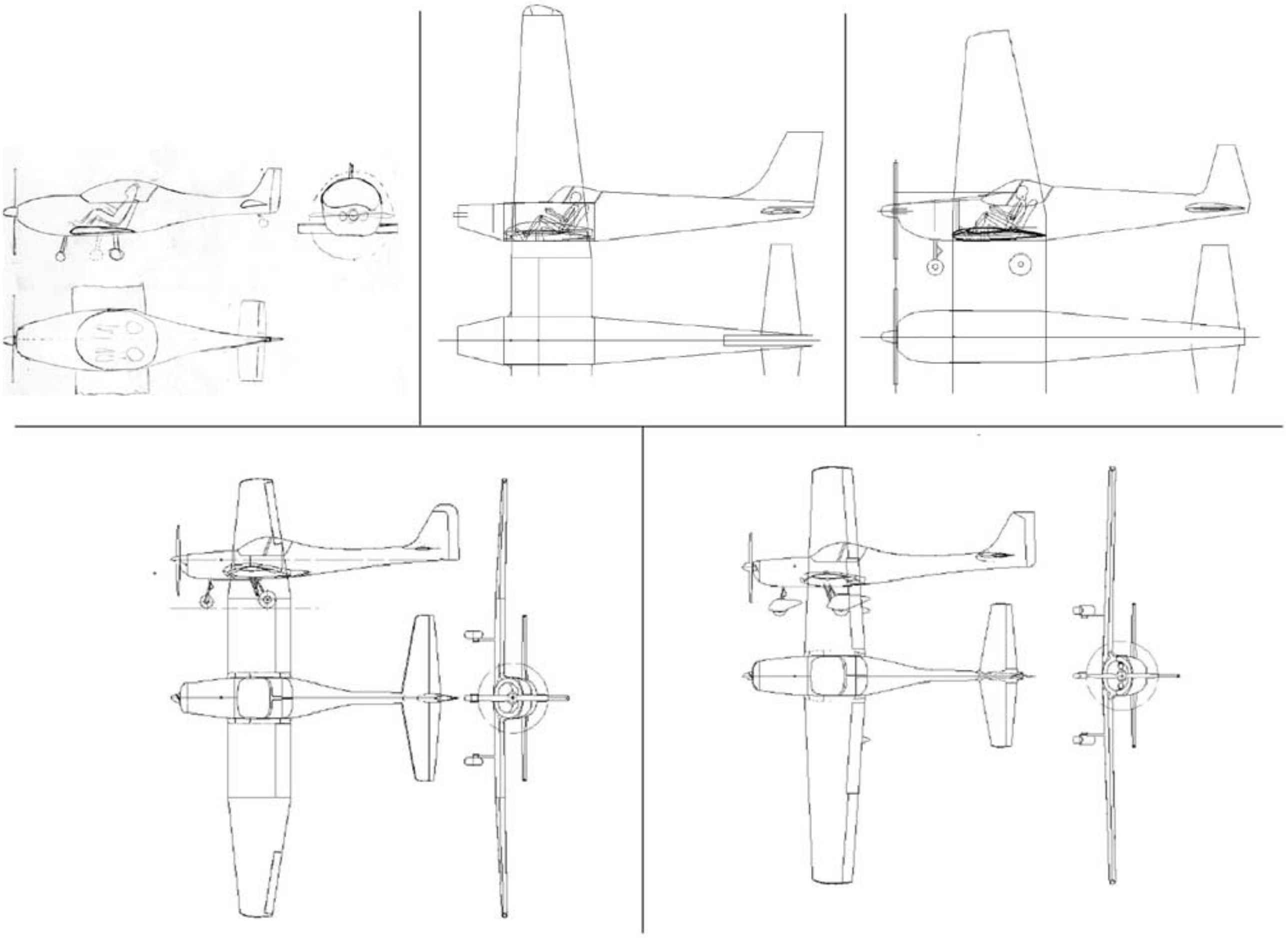

Figure 3 – Chronological evolution of the drawings of aircraft Brati

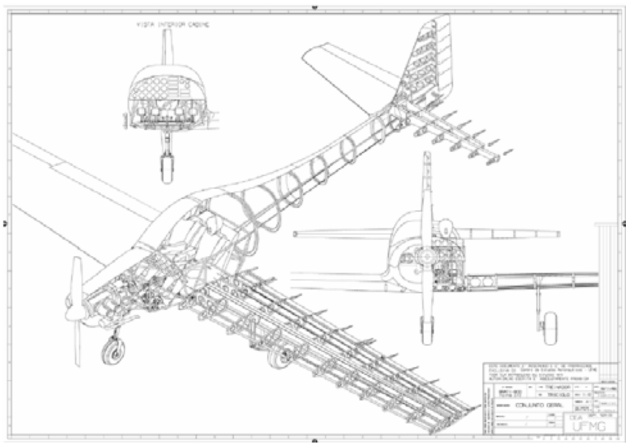

Figure 4 – Three-dimensional detailed drawing of aircraft Brati

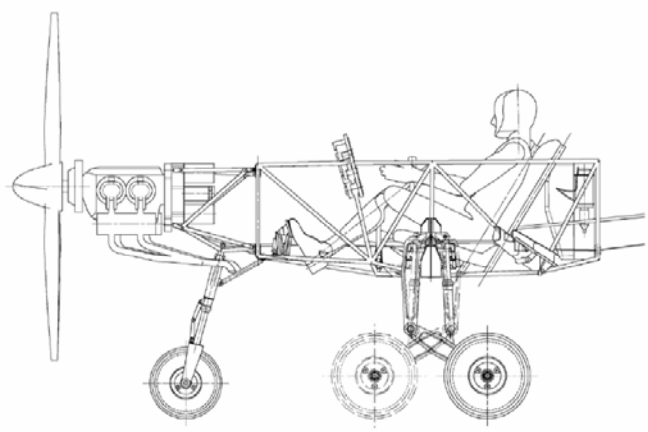

Figure 5 –Detail of the assemblage solution of nose-gear or tail-wheel configurations

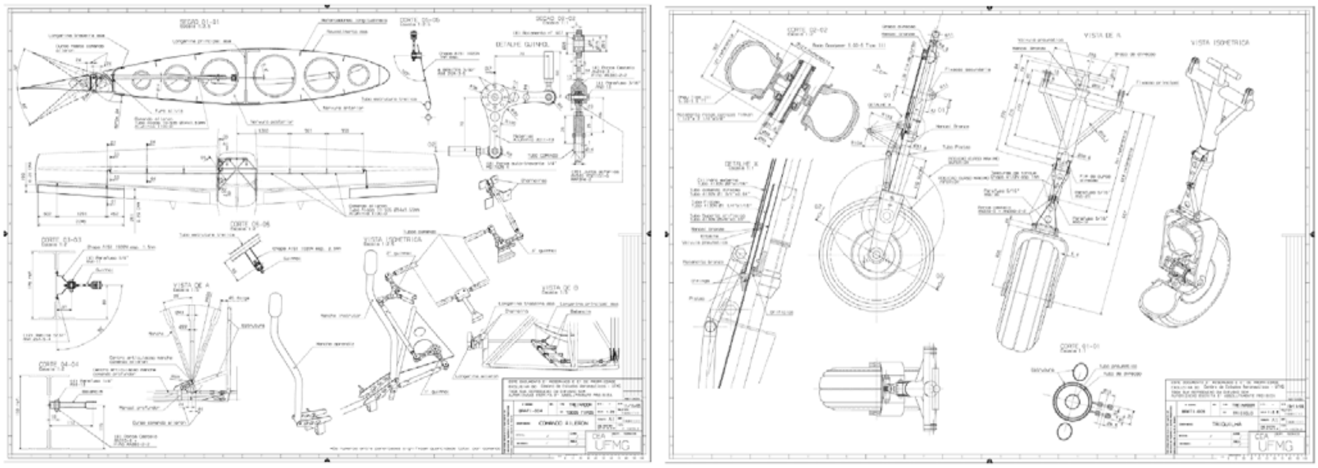

Figure 6 – Detailed drawings for manufacturing of aircraft Brati

Agricultural aircraft – AG-CEA 380 and Urutau

The aircraft AG-CEA 380 and Urutau were designed during the year of 2005 attending to the following design specification:

- load capacity for the agricultural system: 1,500kg or 2,200 liters;
- take off distance: 350m;
- landing distance: 200m;
- maximum leveled speed: higher than 145kt;
- maximum range at sea level with the agricultural system installed: higher than 1,000km;
- basic equipments – DGPS, VHF radio, transponder, VFR, ELT, navigation lights, headlights, cockpit air conditioning, solid dispersion system;
- characteristics: mechanical and chemical robustness, maintenance simplicity, high flight quality, high safety (passive and active) level.

Due to the specificity of this project, it was required to students to execute a detailed research on the equipments for agricultural aircraft operation. This task was performed within the comparative method phase and brought realism to the project, including direct contact with the companies of retail, maintenance and operation of such aircraft.

Figure 7 shows a chronological evolution of the drawings of the agricultural aircraft Urutau, showing the students improvement during the design process. Figure 8 presents the final view of both aircrafts AG-CEA-380 and Urutau.

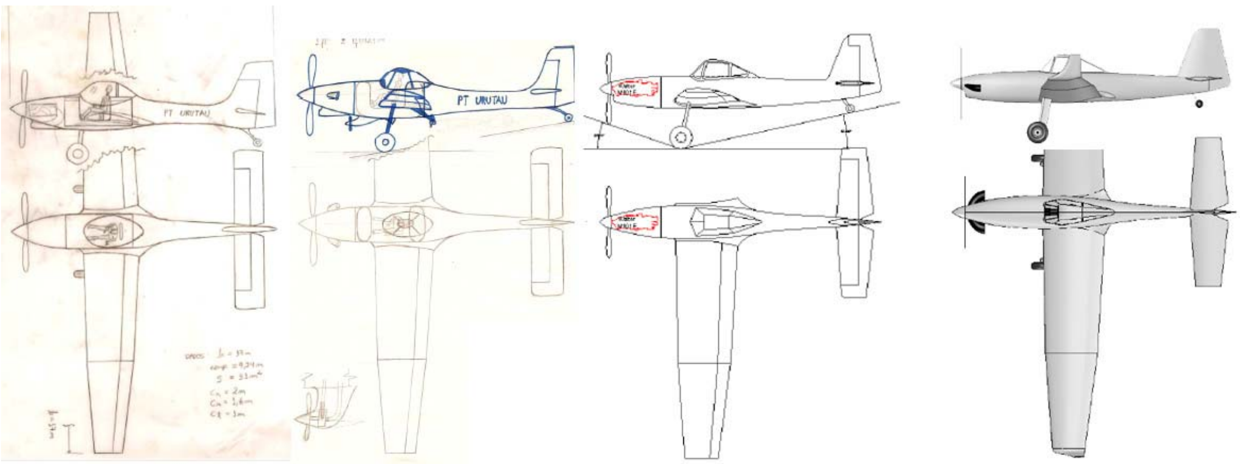

Figure 7 – Chronological evolution of the drawings of agricultural aircraft Urutau

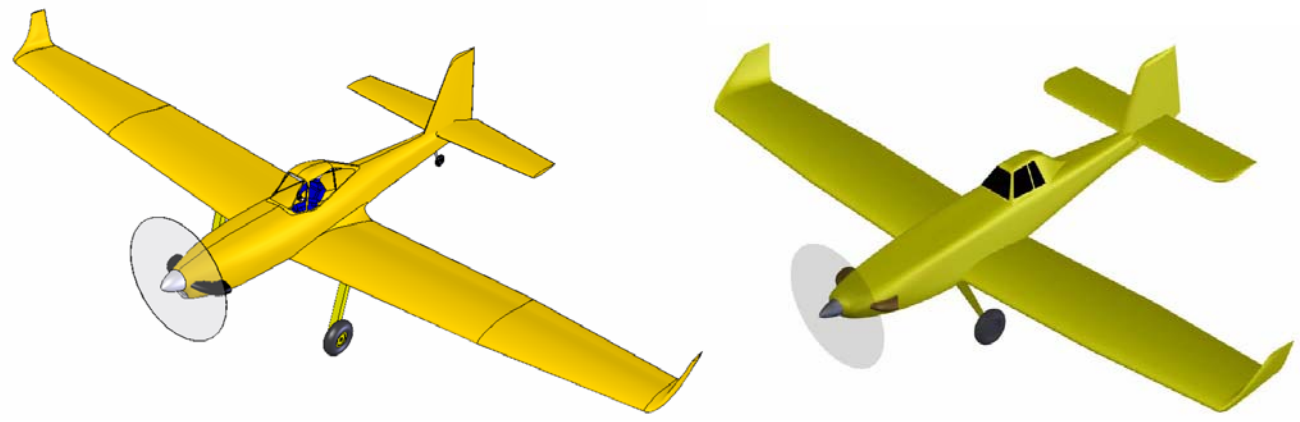

Figure 8 – Final view of the aircrafts AG-CEA-380 (left) and Urutau (right)

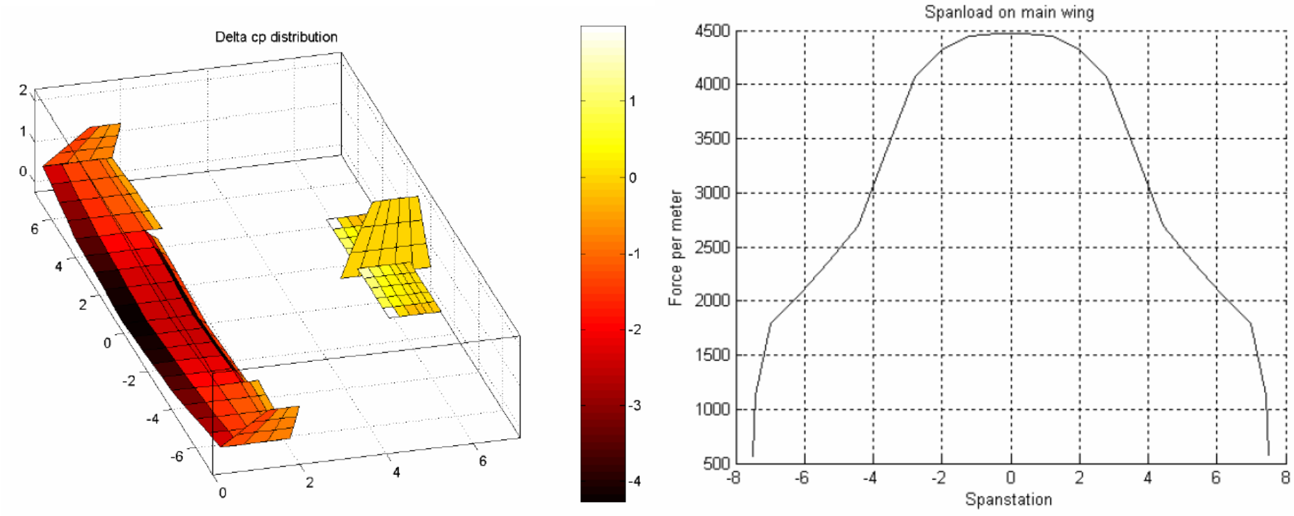

Figure 9 – Aerodynamic analysis of the wing-empennage system of the aircraft AG-CEA-380

Due to the aircraft size, the students selected a turbo-prop propulsion system (Walter M-601 750bhp turboprop engine). The detailed research on the equipments and installation of this engine was included on the design, increasing the diversity of the subjects treated by the students.

It is important to highlight the detailed aerodynamic analysis of the wing-empennage system of the aircraft AG-CEA-380, using Vortex-Lattice computational techniques. Figure 9 shows some results of this analysis that was performed using Tornado Vortex-Lattice code developed by Tomas Melin at KTH, Department of Aeronautical and Vehicle Engineering (Melin, 2006).

The final report of these projects can be seen at the site: http://www.demec.ufmg.br/Cea/projetos.htm

5. Conclusion

A brief description of the methodology for teaching Aircraft Design at the Center for Aeronautics Studies of the Federal University of Minas Gerais was presented. Design phases are and their intrinsic steps were pointed out. Feedback given by the students as well as by the industry was commented.

As example, some details of three recent student projects developed on the Aircraft Design course were also presented. These results show not only the quality of the designers, but also the degree of design detailing achieved. Furthermore, the students are required to develop qualities of leadership and independent/team work, which are hard to teach in regular courses. These abilities allow the students to apply the methodology to other areas of Engineering Design (automotive, naval, space technology, energy, etc.).

The graduate design engineers demonstrate that this methodology is adequate to develop the designers required by the modern Brazilian Aeronautical Industry, which has demonstrated undisputed leadership on the international aircraft market.

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We hope this paper can be, in some way, a retribution to his daring and determination in the creation of this course, his design classes throughout all these years, classes we once attended as students, as well as his ongoing work.

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