

Teaching Airplane Design: A Multi-Level Approach*

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Although the world of design at the university experiences plenty of obstacles for various reasons, it is an absolutely essential part of engineering education. The statement also applies to teaching airplane design, and most academics find it both exciting and demanding. This paper describes the experience of the School of Aeronautical Engineering of Madrid, Spain, in this field. The students have three different levels of involvement in airplane design tasks: first, a compulsory initial design project carried out by teams, focused on conceptual design; second, individually performed final year projects (but only for those ones that have selected airplane design as topic) oriented toward preliminary design; third, in-depth studies, of proper detailed design, developed by a few voluntary students that collaborate with the research staff. The approach seems to be adequate and useful, both from pedagogical and professional points of view, according to the feedback received through the course assessment questionnaire and comments by industry managers. The use of complete CAD systems is not encouraged in an attempt to avoid the students to become mere software users; although some codes are available for aerodynamic and structural computations. A key point in this arrangement is to maintain a synthesis-oriented mind rather than stimulating the already well educated analytical perspective.

INTRODUCTION

MOST academics shall agree with the statement that teaching engineering design is both exciting and difficult. First, current interest in engineering is in high technology and its impact in the performance of systems or devices. Second, it is something new for students, since they have travelled a very long way through different phases of their education, during which most topics are taught with the aim of developing a good analytical mind and not a creative one.

The erroneous opinion that design is neither challenging nor rewarding has contributed in the past to a negative attitude toward design. The old slogan saying that 'design just has to be learned from experience' is, fortunately, out of date [1].

Engineering design is the process of devising a feasible and efficient solution to some specified needs. It is a decision-making process, essentially iterative and interactive, in which basic and engineering sciences are applied to convert resources into real or abstract concepts [2].

The designer has to solve a frequently ill-defined problem and has to reach the best (or one of the best among the many) possible solutions. He or she starts with some initial conception, then performs certain optimization processes usually with the help of a computer-aided design system, and finally has to provide a very complete set of physical magnitudes defining the final design with the appropriate detail for production or use. The

task is so overwhelming that a design team is required even for the smallest components; not to mention a car or an airplane.

According to the former broad description, it is easy to envisage diverse types of design [3]: conceptual design, preliminary design, advanced or detailed design, prototype or tests design, production design, etc. Among them, conceptual design appears to be the most creative or imaginative and, hence, the most difficult to teach.

The world of design at the university has plenty of obstacles for different reasons [1, 4]. There is very little funding for design research and faculty members must find an additional line of activity to establish an acceptable publication level; moreover, no true design journals exist. Also, young lecturers are rarely competent in design, since they lack experience. From the point of view of teaching needs, design requires much more time and effort than regular academic courses; and this is apart from the already indicated fact of dealing with analytical-minded students. Last, most competent designers are in industry and, within the previous framework, it would be very seldom to convince some of them to move to an environment where design is not considered top-level.

In spite of all negative aspects described above, nobody doubts the need of teaching engineering design, particularly in aeronautics. In USA [3–5] as abroad [6, 7] design is a required part of any engineering curriculum. Nevertheless, scholars and designers are denouncing the wrong orientation of some schools that offer curricula leading to scientists but mediocre engineers [8]. It is commonly recognized that students need

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special skills and much tutorial help to be able to integrate their knowledge for designing airworthy, efficient aircraft.

This article describes the experience of the Escuela Técnica Superior de Ingenieros Aero-náuticos (ETSIA), the unique high-level school of aeronautical engineering in Spain, in the field of teaching airplane design. The approach used in recent years consists of three different levels of student involvement: an initial design project, the final year project, and in-depth studies. These levels are considered in some detail in the following paragraphs, but to clarify the situation we comment first on the curriculum and other main features of ETSIA.

All figures and sketches appearing in this paper have directly been taken from students' reports, without additional corrections or changes, except the size of numbers appearing in both axis of co-ordinates for better legibility.

THE AeroEng CURRICULUM OF ETSIA

The School of Aeronautical Engineering of the Polytechnique University of Madrid in Spain, ETSIA, has offered courses since 1928. Historically, ETSIA was created as an independent institution and, as a consequence, its staff had to cover all topics, ranging from basic sciences to pure engineering matters. In spite of merging with other Schools of Engineering in 1971 into the Polytechnique University of Madrid, ETSIA has retained most of its own academic organization. Nowadays, with unique high-level aeronautical studies in Spain, it has grown to a faculty of about 160 staff (half of them professionals of industry lecturing part time) and some 1700 students.

The program has changed over the years to encompass the evolution of needs in different periods of Spanish industry and administration. Currently, the curriculum consists of a six-year syllabus. The first three years are common to all students and deal with mathematics, physics, chemistry, technical drawing, mechanics, materials, strength of materials, thermodynamics, fluid mechanics and electricity. After this first cycle, the students select one among four different options: aircraft; propulsion; navigation and air transport; and airports [6, 7]. Table 1 depicts main features of this syllabus. Enforced by the trend to European homogeneity, the syllabus will change in the near future to a five-year program.

Because of the uniqueness of the academic degree (by law), all students must achieve a minimum level in all topics irrespectively of the option followed; i.e. students in the airport branch also take a course in flight mechanics, but shorter than the one compulsory in the aircraft specialty. It is easy to see that this curriculum largely meets the requirements of USA universities [5, 9].

About 250 new students are admitted each year, with selection based on a competitive national exam, taken by secondary school students that have attended the optional, engineering-oriented curriculum. The drop-out rate is pretty high in the first and somewhat less in the second year, resulting in a figure of around 120 people that are able to finish the course. Although the specified duration is six years for complete studies, most students remain for seven or eight years [7].

For the purpose of this paper it is important to notice that in the last year all students must follow a course in Airplane Design: two semesters for those attending the aircraft option (covering all kinds of airplanes, fairly complete airworthiness requirements and some lectures on structural

Table 1. Curriculum of ETSIA

Common to all options		
FIRST YEAR	SECOND YEAR	THIRD YEAR
Linear Algebra	Mathematical Analysis	Strength of Materials
Calculus	Mechanics	Electricity & Elec. Eng.
Physics	Material Sciences	Fluid Mechanics
Chemistry	Thermodynamics	Mathematical Methods
Technical Drawing	Descriptive Geometry*	
	Differential Geometry*	
Aircraft Option		
FOURTH YEAR	FIFTH YEAR	SIXTH YEAR
Electronics	Manufact. & Prod. Org.	Economics & BA
Statistics	Metals Technology	Airplane Design
Aerodynamics	Flight Mechanics	Helicopters
Structures	Jet Engines & Rockets	Missiles & Spacecraft*
Vibrations*	Aeroelasticity*	Airport Technology*
Recipr. Engines*	Computers & Control*	Air Navigation*
		Air Transport*
		Aircraft Systems*
		Final Year Project

* One semester only

design); and only one semester for the others (transport airplanes only and main airworthiness requirements).

INITIAL DESIGN PROJECT

As a compulsory part of the Airplane Design course in the sixth year, all students are asked to perform an initial design project.

From the pedagogical point of view, the objective of such work is twofold: first, to test and evaluate the application of concepts and procedures of conceptual design taught during the course; second, to stimulate team working, with the advantages and drawbacks of decision taking in groups, which is the usual way in professional life.

This work is carried out in teams of four to six people; this size arises from a balance between the minimum needed for cross-pollination and equilibrium in the decision-making process and the maximum in which responsibility and tasks are still well defined [10]. The teams start from some initial specifications provided by the lecturers, when the course is already running for two or three weeks. Initial specifications normally include type of mission, payload, range at given speed and height, take-off and landing distances, etc. [11–13].

At the end of the course, a report of 50 to 100 pages is presented with main results and conclusions: Table 2 shows the typical index of the report. Additionally, each team of students of the aircraft option must make an oral presentation (the absence of this requisite for all others is due to lack of time). Each report is evaluated separately, receiving a unique mark; which is the same for all students in the team. This arrangement is similar to those reported in literature [11–13].

Some tutorial assistance is available during early stages, mainly to help the teams to becoming organized, to avoiding them succumbing to their fear to the unknown and for preliminary decisions; at later stages the work is performed outside normal course time with occasional need for tutorial help [10, 14]. The experience over the past years indicates that the follow-up is particularly useful for detecting, in due time, wrong decisions leading to erroneous results and grotesque designs.

Main sources of formulae and procedures are

Table 2. Index of the initial design project report

1.	Definition of mission and initial specifications
2.	Existing similar airplanes: selection and tables with main features
3.	Configuration and sizing: design of the fuselage, estimates of main weights, selection of wing loading and thrust/power loading, full geometrical definition of the airplane, three-view drawing
4.	Drag polar curves of the airplane in a given configuration
5.	Performances: study of payload/range diagram or some variable of importance for the airplane
6.	Final comments

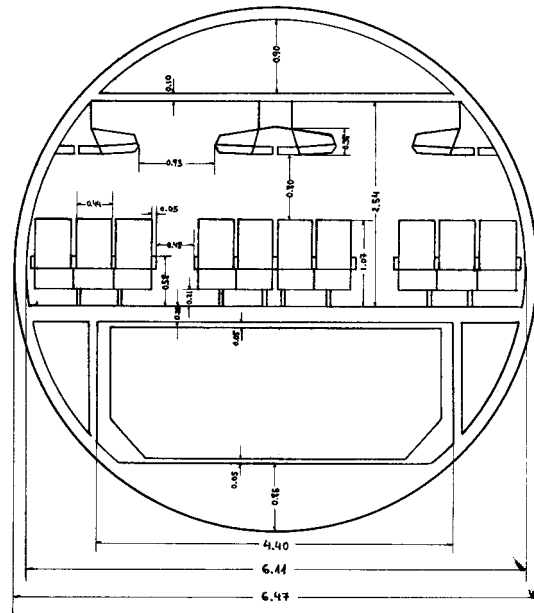


Fig. 1. Cross-section of a long-range, wide-body transport aircraft (dimensions in meters).

well known text books [15–19]. Around 100 variables must be computed: main weights (MTOW, OEW, etc), fuselage and wing geometry, etc. Inevitably, not all variables are obtained with the same degree of accuracy nor receive the same level of attention; for example, the horizontal and vertical tailplanes are determined directly through volume coefficients of similar existing airplanes. Computations are usually performed on PC's with Class I or Class II methods. Extensive use of 2-D plots, with diverse limits and constraints, provide the basis for establishing operating points, deciding among compromises or discussing the results [10, 13, 14].

Some typical results are shown in Figs 1 to 3. The first one exhibits the circular cross section corresponding to a wide-body, long-range aircraft, with all main geometric data; the students have

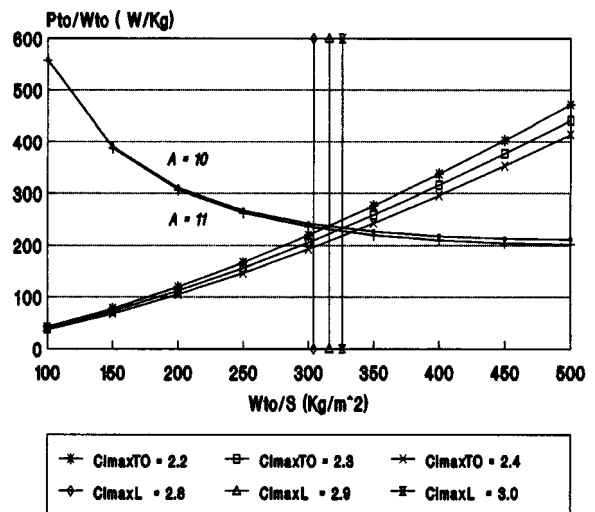


Fig. 2. Available space for design, according to take-off distance, landing distance and cruise speed requirements.

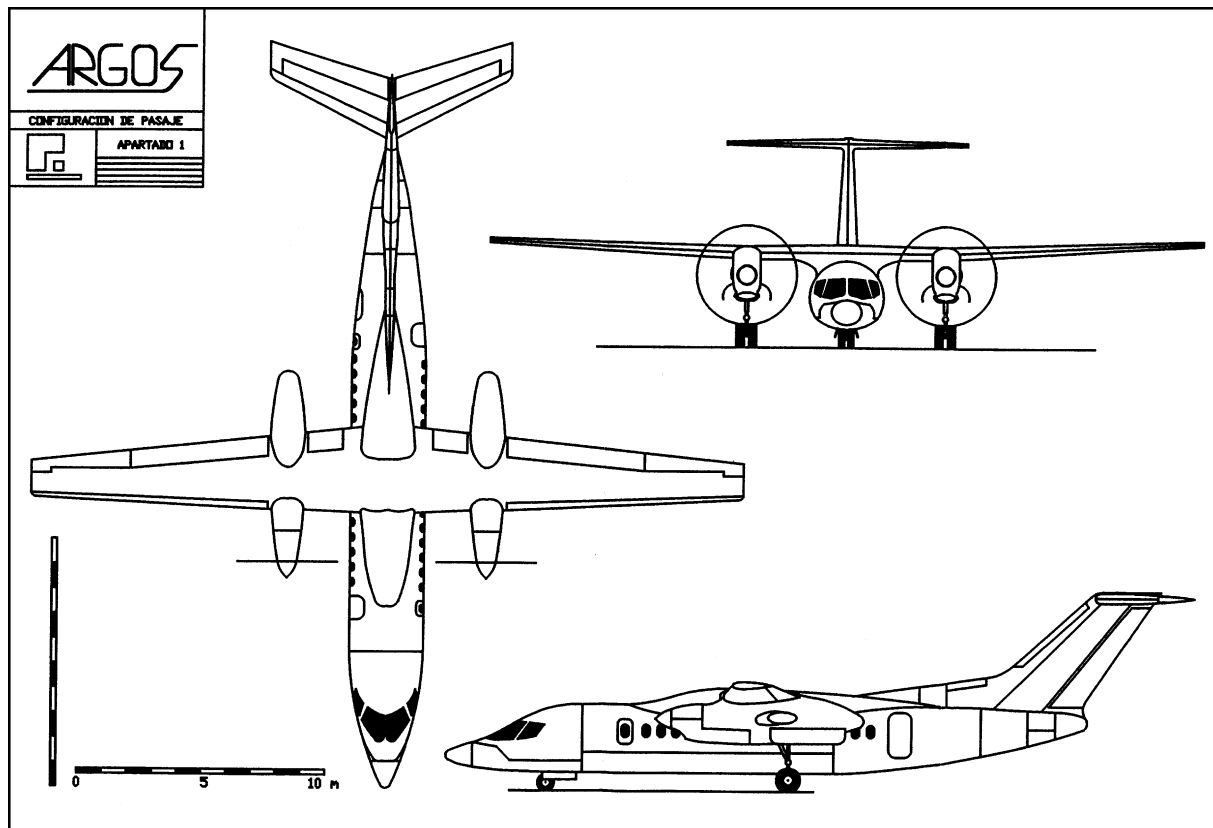


Fig. 3. Three-view drawing of a regional transport aircraft.

selected the same arrangement as in a B747, both in the cabin and the freight hold but, perhaps, the overhead bins are a bit too high. Figure 2 depicts the design boundaries corresponding to three common requirements (take-off and landing distances and cruise speed) in order to establish the wing loading and the power-to-weight ratio of a regional biturboprop. (The team did not represent the second segment climb requirement since it was well below the other limits; it is easy to see that the wing aspect ratio is of secondary value here—it will play its role in the chapter devoted to performance.) Figure 3 is a drawing of another regional aircraft; the academic staff emphasizes the relevance of appropriate relative positions among all main elements: wing, tailplane, engines, fin, landing gear.

Airplane design is essentially an iterative process but only one loop, at conceptual design level, is accomplished within the scope of this work. Optimization is not required, since it would imply a much longer working time and/or the use of complete CAD systems [14, 20]. Students are told not to use any of the well-established CAD codes [13, 20–23] because, although these provide excellent results, the students adopt the attitude of analyzing outputs instead of integrating their knowledge. Moreover, some systems have preference or are better adapted to predetermined configurations. We try to avoid students becoming mere software users, enthusiastically looking at

huge amounts of data without actually choosing, deciding and designing.

It could be said that the procedure adopted for this team work lies in between a 'systems approach' and a 'thinkers approach' [24]. Obviously the students will not always get specific expertise in particular areas, since a synthesis approach is adopted during the whole course. In the Spanish job market it is difficult to foresee the future field of activity of students after graduation; and in most cases they will need more of a good, broad background (and a mind educated to synthesis and problem solving) than having very developed skills in narrow areas. On the other hand, learning to integrate different disciplines and learning to think in a clear, organized manner are top objectives of a course in aircraft design [24].

The feedback on this initial design project, obtained through the Aircraft Design course assessment questionnaire, is extremely satisfactory. The students rate this task as one of the most attractive and important among all types of activities performed during the whole career, and for some 40% of them is absolutely 'number one'.

FINAL YEAR PROJECT

Apart from normal courses, all students must perform their own individual work and present the corresponding report of a compulsory graduation

project, called the Final Year Project. There is a broad range of themes, covering diverse aircraft, engines, airports, etc. Commonly, students select a subject close to his/her specialty. Among those following the aircraft option, around 25 prefer airplane, some 8 are more prone to helicopters, about 6 take spacecraft and satellites, etc. The same group teaching airplane design is also responsible for all Final Year Projects dealing with airplanes.

Regarding its objectives, scope and extension it is a completely different task than the initial design project. The work is individual, much more complete, including certain degrees of optimization and using more sophisticated methods. Most students last more than the normal academic

year to finish the FYP; a lot of time is employed, well in excess of 500 hours, and the final document is a set of three volumes containing a total of some 400–600 pages.

Tutorial assistance is given on a weekly base (an hour-and-a-half per session) but many students ask for extra help, which is offered without any obstacles. Frequent exchanges of ideas, experience and results takes place among staff and students in group monthly meetings.

The theme is freely decided by the students, and staff intervention is limited to avoiding too similar aircraft being designed, thus avoiding either undue competition or too much work sharing. By far, transport airplanes and business jets are the most

Table 3. Index of a final year project (transport airplane)

-
1. CONFIGURATION AND SIZING
 - 1.1 Definition of mission and initial specifications
 - 1.2 Existing similar airplanes: tables with main variables
 - 1.3 Configuration: criteria to select an initial arrangement
 - 1.4 Fuselage sizing: full definition
 - 1.5 Determination of main weights: MTOW, OEW, MPL, MZFW
 - 1.6 Design point: wing loading versus thrust or power loading
 - 1.7 Wing sizing: aspect ratio, taper ratio, relative thickness, type of airfoils, high lift devices
 - 1.8 Three-view drawing
 - 1.9 Sizing of horizontal and vertical tailplanes
 - 1.10 Landing gear arrangement
 - 1.11 Detailed weight estimation: centre of gravity for different conditions
 - 1.12 Conclusions on Part I
 2. AERODYNAMIC STUDY
 - 2.1 Wing lift: lift distribution, twist, effect of high lift devices, maximum lift coefficient, etc
 - 2.2 Trimming: aerodynamic center of the airplane, selection of wing and horizontal tailplane incidences
 - 2.3 Drag: parasite drag of wing, fuselage, tailplanes, nacelles; induced drag of wing, trim drag
 - 2.4 Polar curves: drag polar, L/D versus lift coefficient, etc
 - 2.5 Summary of aerodynamic properties
 3. PERFORMANCES
 - 3.1 Power plant selection
 - 3.2 Power installation: available thrust or power
 - 3.3 Horizontal flight: cruise conditions
 - 3.4 Climbing performances
 - 3.5 Take-off and landing performances
 - 3.6 Payload/range diagram
 4. STABILITY AND CONTROL
 - 4.1 Stability derivatives
 - 4.2 Static longitudinal stability
 - 4.3 Longitudinal control
 - 4.4 Lateral-directional stability and control
 - 4.5 Dynamic longitudinal stability
 - 4.6 Dynamic lateral-directional stability
 - 4.7 Conclusions on Part II
 5. AIRWORTHINESS REQUIREMENTS ON STRUCTURAL LOADS
 - 5.1 Flight manoeuvre and gust envelopes: two weights and two heights
 - 5.2 Loads due to elevator, ailerons and rudder deflections
 - 5.3 Ground loads: landing at diverse conditions
 6. STRUCTURAL DESIGN AND ANALYSIS
 - 6.1 General description of the airplane structure
 - 6.2 Structural modelization of a main part
 - 6.3 Loads acting on the chosen main part
 - 6.4 Sizing of different components (skin, spars, stringers, etc)
 - 6.5 Stress and strain fields, and macroscopic deformation
 - 6.6 Conclusions on Part III
 7. CONCLUSIONS

REFERENCES

demanded; however, there are always some combat aircraft, trainers or small airplanes.

Table 3 summarizes the content of a Final Year Project. The resemblance of the names of first chapters and subchapters with the index of the initial design project is only apparent. Understandably, it covers many more variables, which are determined with higher accuracy.

Initial specifications are similar to those already indicated earlier, but more detailed or more open. For example, it is normal to include diverse cruise conditions, two or more points of the payload/range diagram, the requirement for extended range operations for twins, and so on and so forth.

The first stage includes the justification of the mission and other main initial features or specifications of the airplane to be designed, based on prospective studies published in the literature [25, 26], including journals and proceedings.

Trade-off and parametric studies are carried out, primarily for weights, performances, and geometry of fuselage (length, diameter, diverse cabin arrangements, freight hold, etc) and wing (aspect ratio, taper ratio, engine location, high lift devices). As in the initial design project, the use of CAD systems is restricted. Nevertheless, some software packages for aerodynamic and structural computations are available to provide certain specified results but the students must

develop their own computer codes to determine important features of the airplane. Again, the iterative nature of an aircraft project must be constrained due to lack of time, although some optimization is accomplished with just a few variables.

The following comments describe some graphical results. Figure 4 shows the internal arrangement of a 130-seat, single class, medium-range (2500 nautical miles) biturbofan; at the beginning the student decided on a large seat pitch in view of the relatively long range for this type of aircraft, but in the last version of his report the one-class capacity provided seating up to 136 with a seat pitch of 86 cm.

Figure 5 includes additional (wing planform effect only) and basic circulation distributions (wing planform, flaps, twist, and aileron effects) in the swept wing of a 150 seater airplane; those distributions are important to understand the aerodynamics of the wing and in particular to determine vortex-induced drag and the maximum lift coefficient.

Figure 6 sketches the modelization of the wing structure and the forces acting on the rib-spar joints; the magnitude of forces are determined in accordance with the most critical situations foreseen in the airworthiness requirements.

Lastly, Fig. 7 is an example of the weight versus

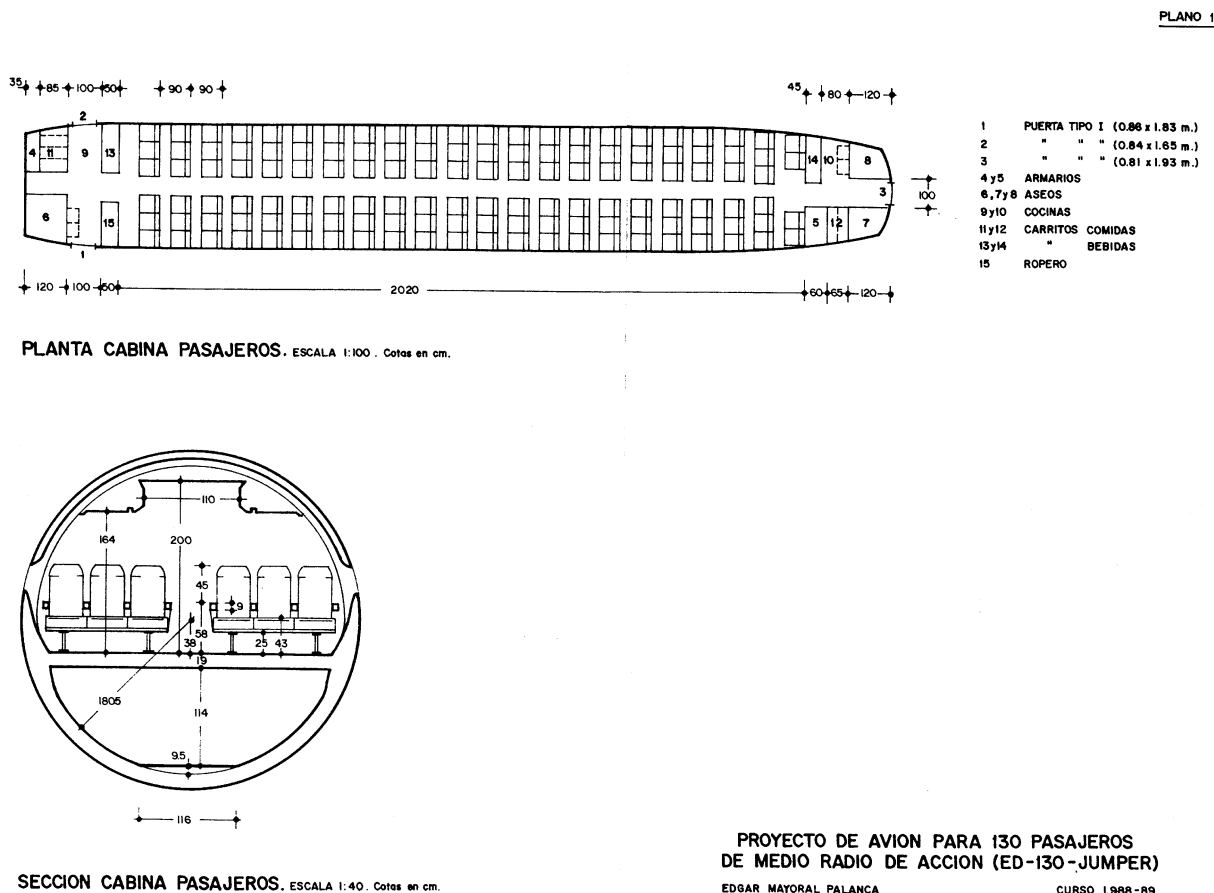


Fig. 4. Cabin arrangement of a 130-seater class, medium-range biturbofan. Dimensions in centimeters. Legend in upper right corner: 1 to 3, type I doors; 4, 5 and 15 wardrobes; 6 to 8 toilets; 9 and 10 galleys over trolleys 11 to 14.

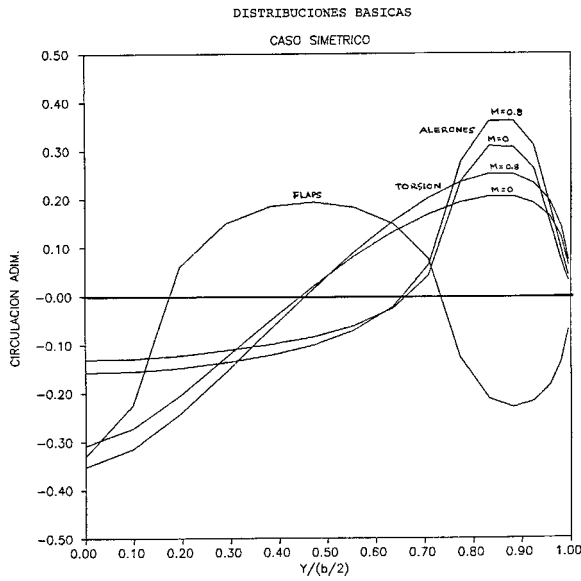


Fig. 5. Basic non-dimensional circulation distributions of the swept wing of a medium-size transport airplane. Symmetric case due to twist (torsion) flaps and ailerons (alerones) deflection.

center of gravity graph used for definitive trimming; the airplane exhibits a too large centre of gravity travel, and the student was asked to suggest adequate changes, either in detail (location of masses) or overall (configuration).

The last stage, devoted to self-evaluation and conclusions, is of extraordinary importance. A key point is not only to comment on the results, but to know the whys of the main findings and outputs. The student must indicate appropriate actions to correct undesirable results.

It is important to note that for unknown reasons the students are not keen to work on structural aspects of the airplane or on the diverse systems. This may be due to the nature of the work, to the arrangement of the curriculum (see Table 1), or to the fact that structural design and analysis have a late chronological position in the Final Year Project.

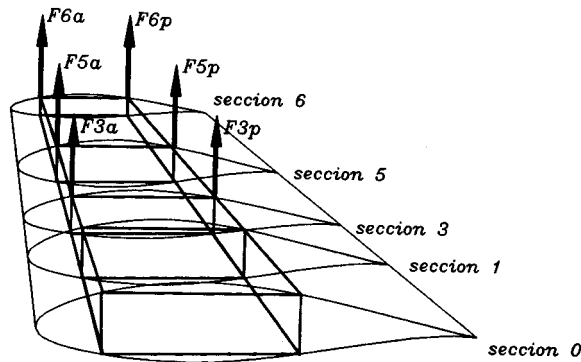


Fig. 6. Simple sketch of wing structure, showing equivalent concentrated loads. Section 0 is the plane of symmetry; section 1 corresponds to the wing/fuselage intersection; section 3 is the nacelle position; section 5 is at the flap/aileron boundary; section 6 is at the outer aileron boundary.

VARIACION Xcg

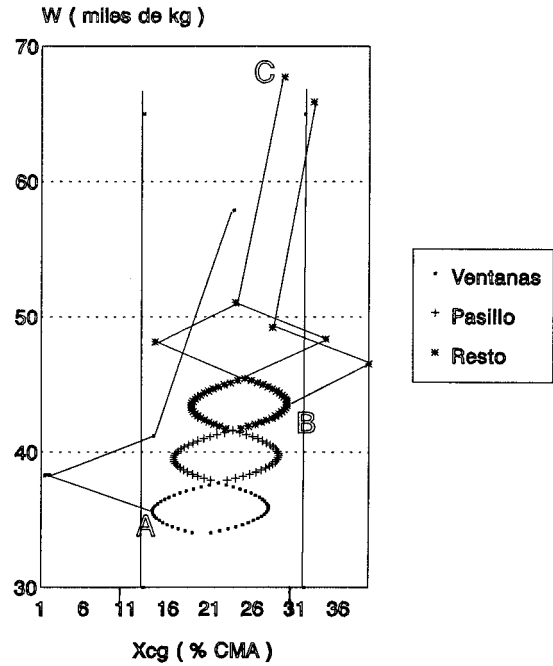


Fig. 7. Weight versus cg plot according to the window seating rule in a medium-size transport airplane. × window; + aisle; * center seat.

IN-DEPTH DESIGN STUDIES

In some cases it happens that the topic of one of the Final Year Projects is very close to a research theme of the staff. Then, the particular student is offered the opportunity to participate in this research, developing a special stage for his FYP, always within the overall scope proper of his FYP. Since this rarely occurs, only one to three students per year benefit from this opportunity. Of course, most students benefit from the material prepared in research work, even though they have not participated in its development.

The themes are very diverse, depending upon interests of industry and the preferred lines of activity of government funding bodies. Thus, they are related to aerodynamics of wings with high-lift systems [27], aerodynamics of complex configurations [28], conditions for optimum cruise [29], performance and productivity of ultra-high capacity airplanes [30, 31], the impact of emerging technologies, etc. Figure 8 depicts the pressure field of a three surface ultra-high capacity airplane.

Fairly complex analytical and numerical methods are used as a necessary approach to those tasks. In recent times, structural design and analysis has started as a new line of activity and, hopefully, after a few years it will reach a similar level of output as in the aforementioned areas.

It is easy to understand that the participation in a research project is enthusiastically accepted by students; but due to lack of staff time and appropriate

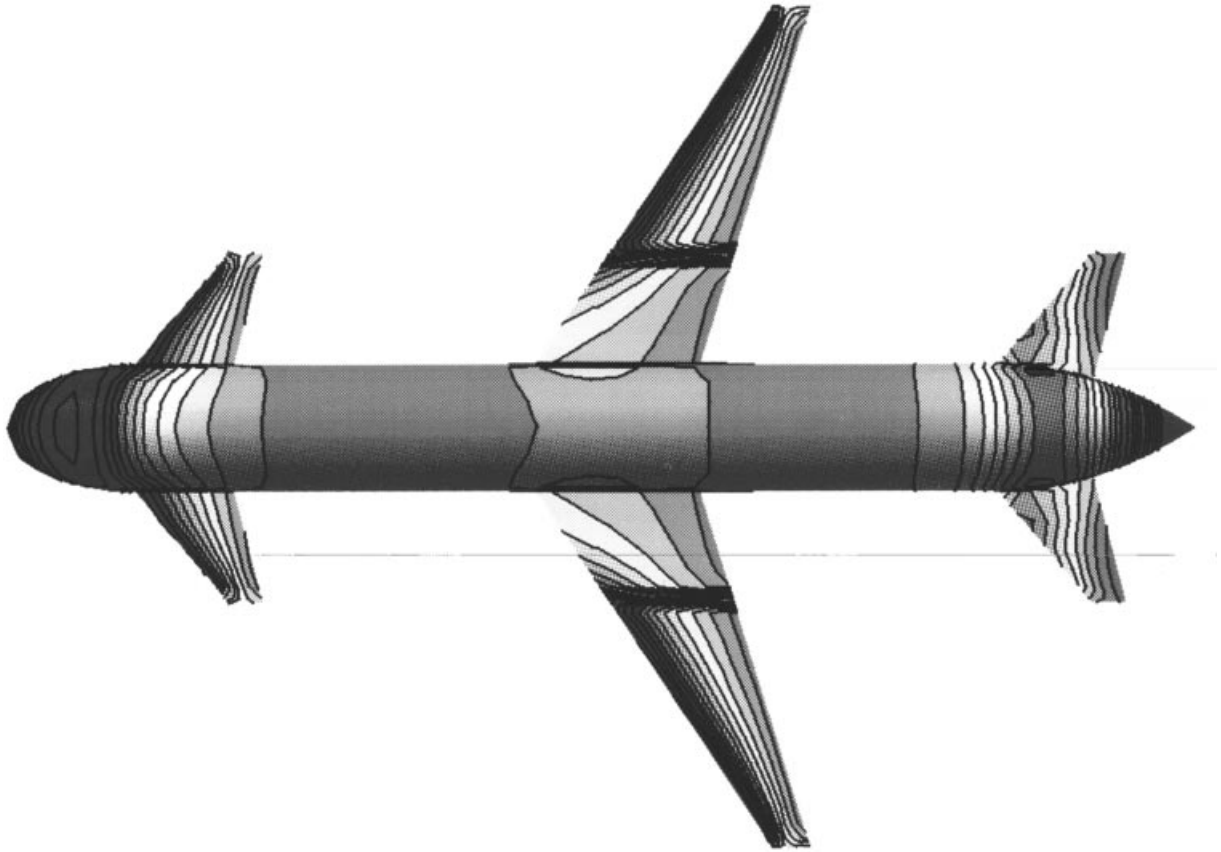


Fig. 8. Isobars (top view) of a three-surface ultra-high capacity airplane.

themes the number must be limited for undergraduates. Incidentally, ETSIA offers also a Doctor of Engineering program that is followed by about 5 to 10 engineers per year, and, from time to time, one is also involved in design-related works.

CONCLUSION

Education in airplane design is receiving a great deal of attention at the School of Aeronautical Engineering of Madrid, Spain. Three distinct levels of involvement in design tasks are provided to students: first, a compulsory project carried out in teams of 4–6 people with limited extension but clearly focused on conceptual design; second, individually performed Final Year Projects, only for those students that have selected airplane design as a topic, oriented toward preliminary design and covering most main items; third, in-depth studies, similar to advanced or detailed design tasks, developed by very few students that

voluntarily (and enthusiastically) participate in the research effort of the airplane design staff.

Both from the pedagogical point of view and from the professional perspective the experience seems to be adequate and very useful; but with the noticeable drawback of being a very hard way of learning, for the simultaneity with a dense final year.

On the other hand, the use of complete CAD systems has been somewhat restricted until present in an attempt to avoid enhancing software user mentality; although some codes are available for aerodynamic and structural computations. The students need not any stimulus to work with computers; even, it could be said that they need some refraining. In a near future new codes shall be added to the airplane design library, but just to accelerate the computing process.

From the staff's perspective the key point is to maintain a synthesis-oriented or integrating creativity, as well as developing problem solving skills, rather than feeding the well educated analytical mind.

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