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Modular Aeroplane for Education in Flight Mechanics*

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This paper explains how to set up a practical experiment to teach the mechanics of flight by means of a modular aeroplane, i.e., an in-field configurable aeroplane that can be designed and assembled by the student for specific mission requirements. The concept comprises a catalogue of modules including pure and aileron-mounted lifting surfaces, propulsion, vertical surfaces, longitudinal extensors, landing supports and other smart modules, all with common structural and electrical interfaces. A software tool is able to quickly assess, using a vortex lattice method, the feasibility of flight and the proper position of centre of mass. Once the aeroplane is built, the parameters and flight path can be uploaded onboard and tests can be performed. Real time and playback monitoring allow the student to check if a selected configuration performs appropriately with respect to the requirements. In addition, a set of simple practical exercises and the expected results are proposed in the paper.

Keywords: aeronautics education; mechanics of flight education; modular aeroplane; unmanned aeroplane; vortex lattice; outdoors experiment; practical education

1. Introduction and objectives

In most universities aeronautical engineering programs offer flight mechanic courses, run after those of fluid mechanics and aerodynamics; the interrelationship between them is obvious. Normally, the subjects include a balance between theoretical and practical contents.

Focusing on practical exercises, facilities to measure fluid magnitudes and to show the applications of Bernoulli's equation, the Venturi effect, pressure drop in tubes, laminar and turbulent flows, heat exchange, the Coanda effect, diffusers and nozzles, compressors and turbines, etc. are typically found in fluid mechanics laboratories. For aerodynamics, the wind tunnel [1, 2] is an important element for providing students with a whole array of exercises to identify the basic and advanced mechanisms to produce and control lift and associated drag and moment with a multitude of airfoils.

On the other hand, computer calculus and simulation has undoubtedly contributed substantially to the understanding of theoretical principles. Remarkable effort has been put into providing models for airfoil design [3, 4], performance databases [5] and software integrating both [6, 7]. Evidently, beginner courses emphasize the study of potential flow, whereas the complexity of boundary layers and viscosity, although introduced, is kept for later courses.

However, this structure is difficult to maintain in studies on the mechanics of flight. The experimental work rarely includes small aeroplane flights that allow the passenger/student to see and feel the effects of stall, adverse yaw, shear wind and Dutch roll. Instead, practical work is reduced to calculus and flight simulations, sometimes with some hardware installed in the loop [8]. Sometimes model aircraft are designed and built to show certain flight characteristics, but there is insufficient time for the student to play a significant role in the process. This, together with the fact that he/she is not able/allowed to pilot the model, makes the experience quite poor; however, the potential of the method has been confirmed [9].

Modern mechatronics technologies allow the development of a facility for flight mechanics education based on a modular model aircraft equipped with the appropriate sensors to provide the student with comprehensive information on onboard parameters and relate them with his/her design and en-route decisions. The model, being safe, needs to be easy to fly, maintain and repair and, of course, to be affordable.

2. System concept

The idea of modular or configurable aircraft has been previously exploited. Most designs allow one to change the configuration of the aircraft at the time of manufacture or transportation, but not while it is in operation.

The aim has been to reuse the designs, manufacture tools and maintenance facilities. There are some initiatives in [10] to build flying toys where damaged parts can be replaced or detached elements to ease storage (these are in the hobby market). A more interesting proposal is discussed in [11], where the joining of several identical aeroplanes allows more efficient flight as a whole. The current project takes this idea much further, to small basic modules, to be able to fully configure the aircraft and therefore its performance.

What is proposed here is a catalogue of aero-

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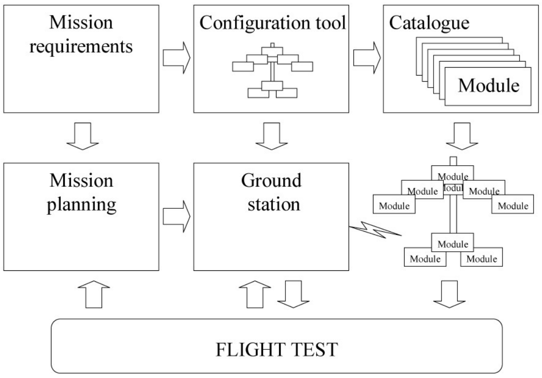

Fig. 1. Logic of the experiment.

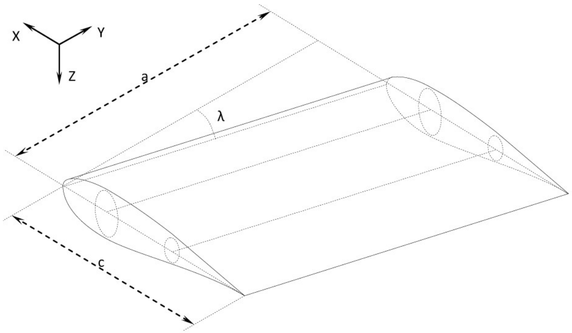

Fig. 2. Lifting module.

dynamic-shaped modules (Fig. 1) that can easily be assembled into a full aerial vehicle, able to fly in automatic or manual modes. The selection of modules and their configuration allows the student to build, without the effort of construction, a wide variety of aeroplanes, whose design depends on the requested exercise.

This modularity also protects against possible damage during hard landing manoeuvres, since replacements are quick and, hence, the model availability is very high.

A modelling tool estimates if the selected configuration is feasible and, if so, it uploads the flight parameters to the onboard computer so that the system is ready to carry out the test under real atmospheric conditions. A mission planning task is needed before the test is carried out, to translate the mission requirements into aircraft commands and flight control definition. These data are transferred to the ground part of the model, which is in charge of managing communications with the aircraft, sending commands and showing its telemetry in real-time, and storing the full state vector for future playback. The concept can be completed with a weather mini-station, which is affordable and easy to install in the surroundings of the operation area.

The catalogue of modules includes pure and aileron-mounted lifting surfaces, propulsion, vertical surfaces, longitudinal extensors, landing supports and other smart modules (onboard processor and avionics), all with common structural and electrical interfaces. The software tools are simple and can be run on a laptop, to allow in-field operation.

3. Catalogue of modules

3.1 Basic lifting module (Fig. 2)

The basic module is a wing section with two mechanical interfaces, corresponding to streamlined profiles that provide the thickness, the chord and taper of the module and, possibly, certain sweep, twist and dihedral angles. A covering skin encloses a space in which other pieces of equipment can be installed and that defines the final aerodynamic form of the module, which can be fitted with more internal ribs for stiffness. The along-wing dimension, from initial to end interfaces, contributes to the wingspan. Port and starboard versions of the module need to be available for symmetric configurations.

The module provides mechanical interfaces that are compatible with the rest of the modules, always in a male–female fashion so that other modules can be added to the chain. The simplest interface, used to attach the wings to the fuselage in aeroplane models, is based on a bayonet–hole coupling; inserting the modules in a common carbon fibre tube or rail is also possible.

Internally, this structural module has to be prepared to support and transmit aerodynamic, gravitational and inertia forces as well as those imported through lateral interfaces. The construction of the module can follow certification standards but, for these training purposes and low-cost versions, the techniques/materials used in modelling have been used: foam, balsa and polymer sheets.

Although there are no electrical components inside the model, the module has to be able to transfer power and data from one side to the other, so cables, male–female connectors and passages need to be provided.

3.2 Lift control element (Fig. 3)

Like the basic module, this also provides a moveable structure that is able to change the air flow around the airfoil, hence providing control over the aerodynamic forces. The model can be used as an aileron, rudder, flap, airbrake or a combination of them.

Now, the internal servomechanisms require electrical power and commands, which are provided by the power bar (cable) and the common data bus, replicated inversely on both sides.

More sophisticated versions of this module could

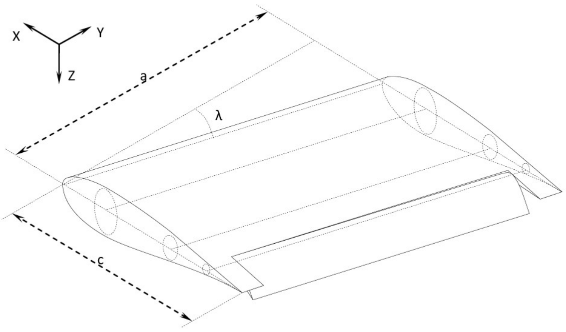

Fig. 3. Lift control module.

implement leading edge flow control elements, dihedral and torsion angle control and other mechanisms to morph the shape of the wing, always under the control of the command bus.

3.3 Wing terminators

This module provides a blunt wing tip that favours the aerodynamic characteristics and encloses the internal structure of the wing. This item does not allow the addition of any new modules to the wing.

The module can include lights, powered from the electrical interface. Should the data bus request a terminator, this module provides it.

3.4 Propulsive module (Fig. 4)

The propulsive module is the thrust provider; this can be any of the known technologies applicable to this size of aeroplane: propellers (electrically or piston driven) and jets.

The simplest case is the electrical motor, normally brushless and with an integrated DC regulator/controller. The power is taken from the main bar and the thrust command from the data bus. The propeller may be installed in a pushing or pulling position.

In the case of a reciprocating engine, a fuel tank is necessary; this can be installed in a neighbouring basic module or an additional ad-hoc module. Also, a servomechanism controls throttle position from the commands received by the common bus. This kind of engine requires electrical filters to be implemented to prevent the export of noise to the rest of the lines.

Jet engines are more powerful and complicated, but still conceptually allowed by the system.

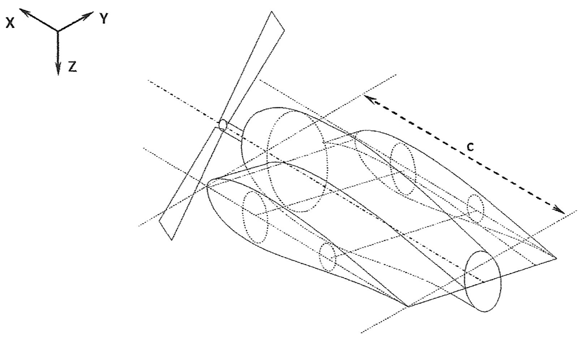

Fig. 4. Propulsive module.

3.5 Other structural elements

A number of standard or custom structural elements can be envisaged. For example, vertical stabilizers or winglets can be added with the element shown in Fig. 5, where a special element has three mechanical interfaces, one to attach itself and two more to continue the chain horizontally and vertically. The vertical stabilizer is able to provide lateral aerodynamic forces with respect to the mechanical interface. It may or may not contain elements for aerodynamic control.

A longitudinal extension (Fig. 6) is a mast that replicates the mechanical and electrical interface in a backward position (or forward) of the wing, allowing the joining of new elements to support flight control (elevators, rudders, canard, etc.) or alternative aeroplane configurations (Figs 7–9).

Other examples of structural elements are fuselages, landing gears, catapult attachments, etc., always under the same mechanical and electrical chainable scheme.

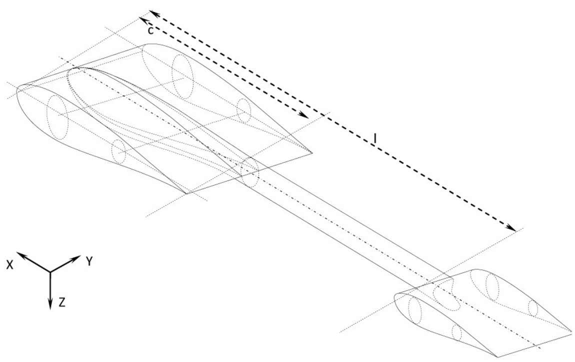

Fig. 5. Longitudinal extension module.

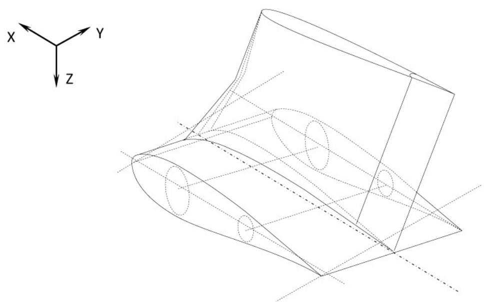

Fig. 6. Longitudinal extension module.

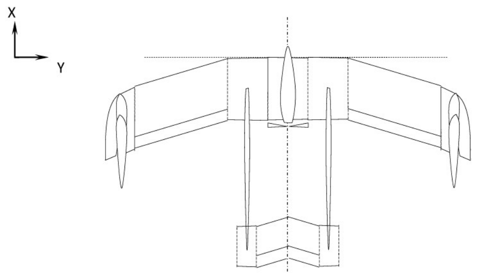

Fig. 7. Example of single-engine airplane with V-tail.

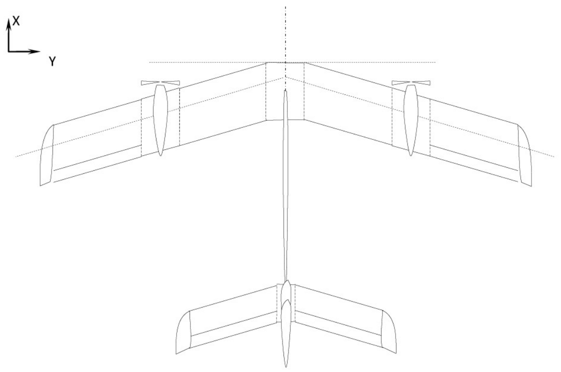

Fig. 8. Example of bi-engine airplane with conventional tail.

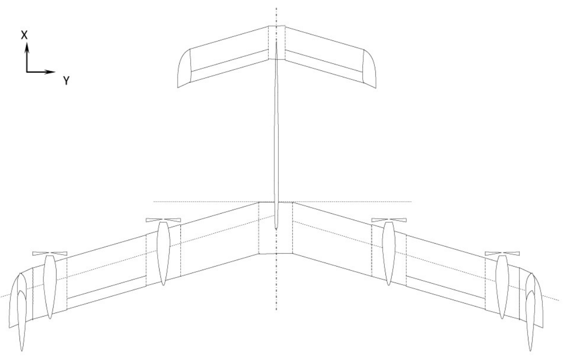

Fig. 9. Example of tetra-engine canard airplane.

3.6 Avionics and electrical configuration

Avionics is treated as a non-structural module that needs to be attached to structural ones where there is room to do so. This flexibility is often used to meet centre of gravity constraints.

Thus, this module provides electrical power, onboard processing capabilities, data bus control, navigation avionics, communication management and other non-structural elements, including possible payloads. The architecture is depicted in Fig. 10.

4. Performance assessment

Prior to the experiment, the student should be able to understand the basics of aeroplane aerodynamic design, the impact of the selected configuration on

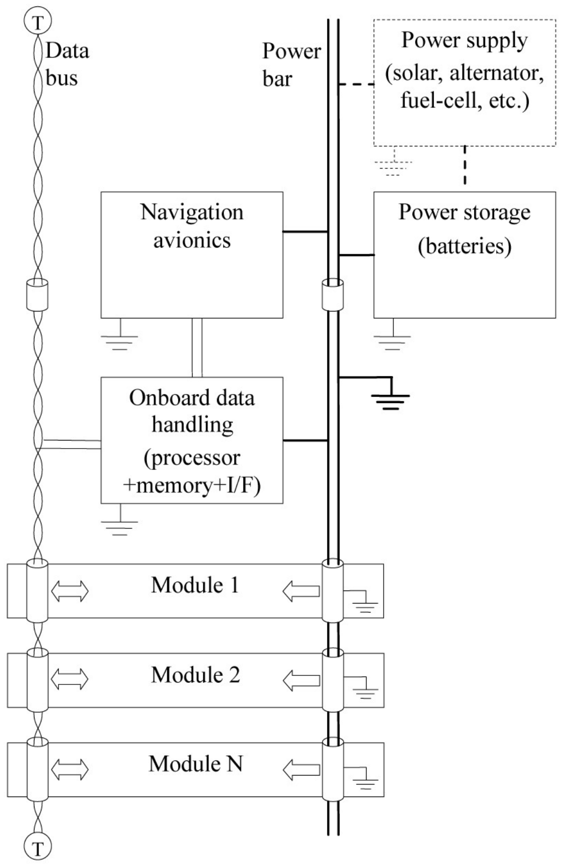

Fig. 10. Electrical architecture onboard.

performance and the methods of evaluating the flight stability and control [12, 13].

In addition to the theoretical classes on thin airfoil aerodynamics and foundations of flight mechanics, the available computational methods [14, 15] are reviewed, with special attention to the Vortex Lattice Method (VLM), widely used in preliminary design phases of subsonic aeroplanes.

The grounds of the VLM is the solution of Laplace's equation by a combination of vortex singularities. Although good VLM open codes [16, 17] are available and well validated for the assessment of aircraft performance, a customized user-friendly software tool has been developed to apply the computational method easily to the educational aircraft model and to help with the task of configuring it. In this way, the user is allowed to quickly select the modules to be included in the requested mission and their distribution throughout the vehicle.

The system imports many available databases with aerodynamic profile information, allowing custom designs and alternative flight configurations. The tool has been tested against Tornado [16] code, showing good matching for lift and induced drag coefficients in most of the conventional designs.

The application is also able to estimate the total centre of mass and the inertia tensor, to quickly assess the feasibility of flight; some recommendations on mass centring are automatically issued. The non-dimensional aerodynamic coefficients are calculated and plotted together with their stability derivatives for all the desired positions of control commands.

Once the aeroplane is built, the aerodynamic parameters and the flight path can be uploaded onboard and tests performed. Real time and playback monitoring allow the student to check if the selected configuration performs appropriately with respect to the requirements.

Figures 11–13 show three quick models prepared for simulation. Figures 14 and 15 present two output plots from the VLM calculations, showing how the high aspect ratio model (C) improves the efficiency of the shorter options (A and B). Also, the canard efficiency (B) is better for smaller angles of attack than the equivalent conventional tail configuration (A). The catalogue modules to build models A and C have been physically made in foam and plastic using small fabrication tools, with both numeric and manual controls. The electronics and propulsors have been borrowed from the standard radio-control industry, whereas in-house bus converters provide the common RS-485 data bus. The

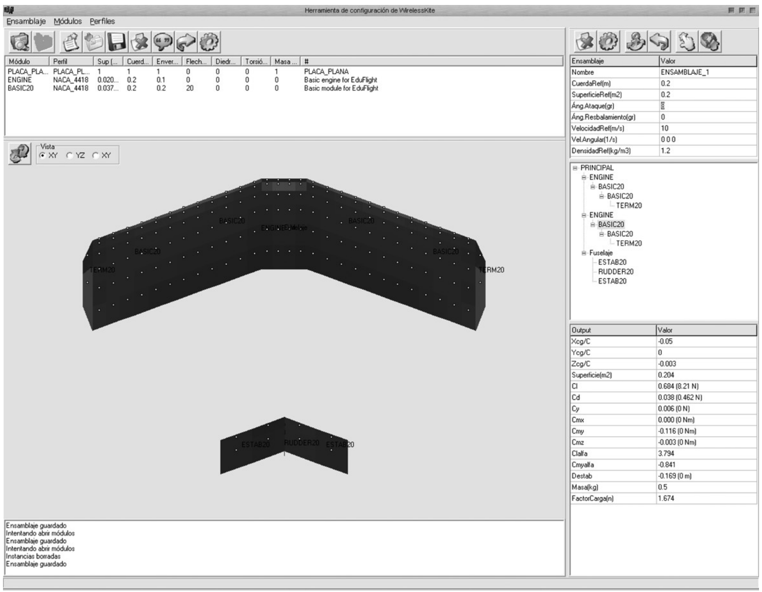

Fig. 11. Configuration tool for model A: Conventional design.

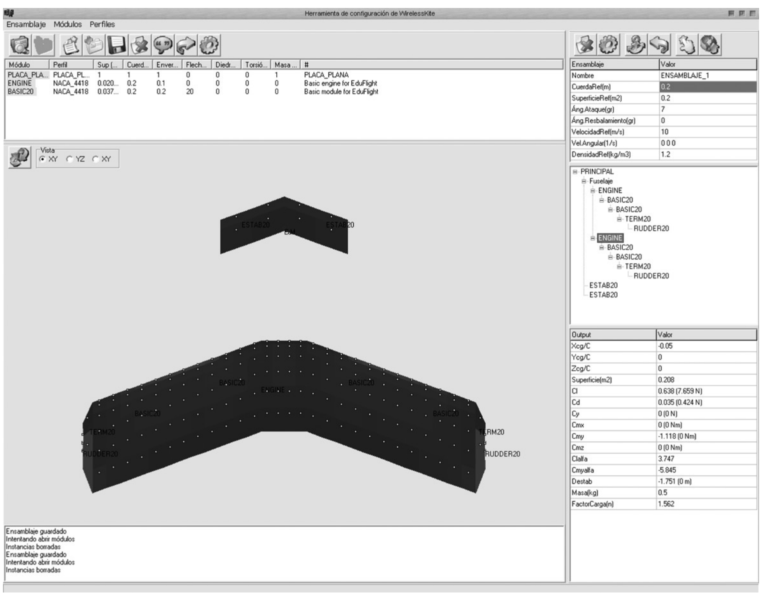

Fig. 12. Configuration tool for model B: canard.

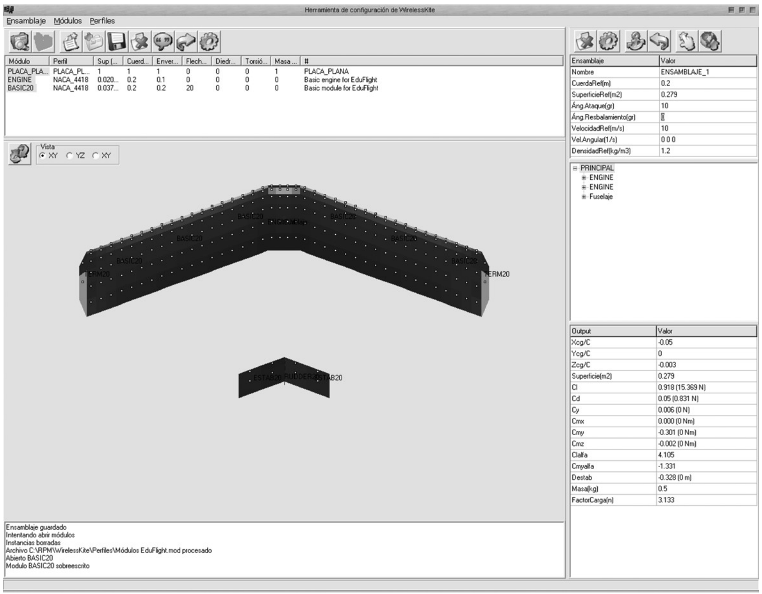

Fig. 13. Configuration tool for model C: high aspect ratio.

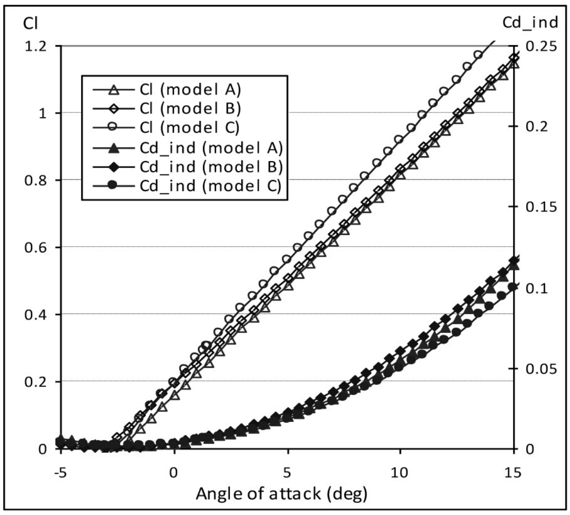

Fig. 14. Lift and drag characteristics for configurations A, B, and C shown in Figs 11, 12, and 13 respectively.

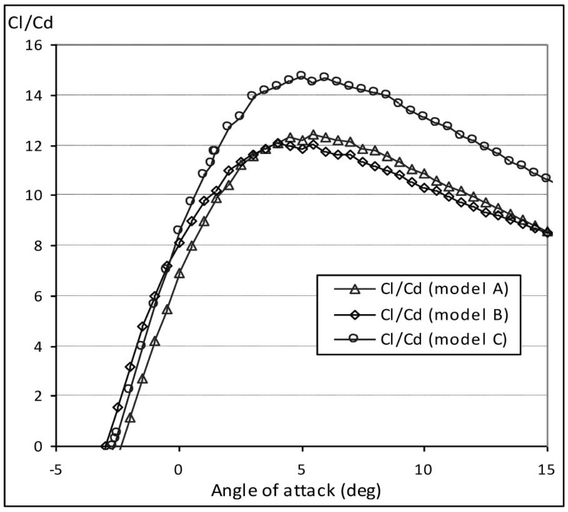

Fig. 15. Lift-to-drag ratio for configurations A, B, and C shown in Figs 11, 12, and 13 respectively.

on-board computer has been programmed in C++ using an open and already available source code from other UAV projects as the starting point.

With all this material, a set of simple practical exercises and expected results are now proposed.

5. Proposed experiments and educational results

The advantage of the system is that the exercises can be run in a very rapid manner. The student is encouraged to test alternative configurations that can be shared around the class as simple files in common directories.

After the familiarization process, a set of requirements are issued and allocated to student groups. These include payload mass, gliding performance, cruise speed, ceiling, top speed, manoeuvrability constraints, ascent path angle, stall, etc. The evaluation is carried out on the basis of the performance parameters estimated by each configuration and a report with the reasoning behind them. A couple of the best configurations can actually be built and flown. Thus, students check and post-process the telemetry files to validate the initial assessment.

Some of the most interesting exercises are a combination of:

- Cruise at maximum speed
  - Two full-throttle, hippodrome circuit, level flights are prepared, sharing all elements and

parameters (including wing load) except the wingspan.
  - Telemetry data allows comparisons between averaged maximum speed in both cases. Several trials with different loads complete the exercise.
- Cruise at minimum consumption speed
  - Different models are test-flown straight at a set of various airspeeds, whereas the electrical consumption history is stored.
  - The analysis shows how it becomes expensive to fly both at high and very low speeds, and where the optimum point is for each model. In addition, higher optimum speeds are achieved with shorter wingspans, while for the same speed, longer wingspans translate into better efficiency.
- Maximum range and autonomy in gliding mode
  - The models are flown without propulsion. The students can program tentative angles of attack to achieve the longest range of a minimum descent rate.
  - Off-line study allows a better understanding of the difference between the two concepts and the impact of wing design on performance.
- Minimum speed and recovery from stall
  - The air speed is reduced progressively whereby the angle of attack is monitored. Several trials allow the estimation of the stall angle and its consequences. When different aerodynamic profiles are available, the exercise can be repeated to observe the diversity of behaviours.
- Response to step control variables
  - Theoretical steps cannot be achieved in real experimentation. However, quick action on the command surface or the throttle can emulate such functions quite well. The reaction of the aeroplane is stored for later analysis.
  - Roll, pitch, yaw and throttle steps are proposed, showing the transient evolution from initial to final conditions. In post-processing of the data, interesting dynamic coefficients can be estimated.
- Phugoid development and analysis
  - The term phugoid refers to the long period of exchange between kinetic and potential energy that an aircraft encounters during its stable flight when a perturbation is introduced [19]. There are approximations to estimate the period of such response [20], which can be checked against the experimentation. As the motion is slow and only slightly damped, the student is able to observe the process and perform comparisons even in real time during the exercise.
- Coordinated and uncoordinated turns
  - Uncoordinated turns (lateral acceleration present relative to the body reference) can be programmed and monitored from the on-board inertial unit. The rate of the mix of roll and yaw commands can be calculated and tested until coordinated turns are achieved.

The work carried out up to now with simple models has produced interesting results from the learning and teaching points of view. The students familiarised themselves with the management of aeronautical hardware in a simple manner, acquiring first-hand competences of flying procedures and improving their knowledge of specific nomenclature; the simplicity of the first models only allows the execution of simple gliding and cruise exercises. The impact of atmospheric conditions on the general performance of the vehicle and in the comfort of the operators was also undoubtedly perceived.

Finally, the involvement and enthusiasm of students when the field experiments are developed are far more intense than in the equivalent class lessons, steepening their learning curve. The modular aeroplane project also boosts other cross-competences, such as team work, negotiation, communication and creativity, the last of these being difficult to stimulate without this kind of initiative.

On the other hand, flexibility is a key issue from the teaching point of view. The modular aeroplane is able to develop from very simple gliding flight to complex acrobatic manoeuvres. This allows the design of uncountable practical exercises that range from basic aerodynamic studies to very complex flight control algorithms.

Currently, a plug-in for the performance assessment tool is being developed to allow students to interactively feel the performance of their model in a flight simulator, prior to the mission planning, in a quick and easy way, and with playback functionality. In the near future, from the data obtained in these exercises, a full six degrees-of-freedom model is to be obtained [21] for conventional configurations. This paves the way for the definition of other more complex missions and educational practices, developing new modules to support them.

6. Conclusions

A small but innovative educational tool has been presented. A catalogue of hardware modules allows the real-time construction of many types of aircraft ready to perform flight practices. Given its modularity, the concept is affordable. A companion tool has been implemented to provide a preliminarily estimate of the aerodynamics of the model, the flight stability and control.

A number of examples have been shown, proposing practical exercises to groups of students that are very attractive and with immediate technical feedback. A flight exercise allows a comparison of estimated and real datasets with many off-line possibilities.

The initiative has developed a real enthusiasm and involvement on the part of the students, improving not only their learning curve in mechanical aerodynamics but also in other cross-competences such as team work and creativity. From the teachers' point of view, the flexibility of the tool enables many types of exercises with a wide range of objectives and complexity.

References

1. M. S. Selig and B. D. McGranahan, Wind tunnel tests of six airfoils for use on small wind turbines, *AIAA 42nd Aerospace Sciences Meeting*, AIAA Paper 2004–1188, Reno, NV, 2004.
2. NASA Astronomy and Astrophysics Advisory Committee (AAAC) *Annual Report*, FY 2002–2003.
3. A. Gopalarathnam and M. S. Selig, A design methodology for low-speed natural laminar flow airfoils, *Journal of Aircraft*, **38**(1), 2001, pp. 57–63.
4. M. S. Selig and M. D. Maughmer, Generalized multipoint inverse airfoil design, *AIAA Journal*, **30**(11), 1992, pp. 2618–2625.
5. J. B. Brandt and M. S. Selig, Propeller performance data at low Reynolds numbers, *49th AIAA Aerospace Sciences Meeting AIAA*, Orlando, FL, 2011, pp. 2011–1255.
6. R. F. Davey, Custom software for design education: an aeronautics example, *The International journal of applied engineering education*, **5**(3), 1989, pp. 383–389.
7. C. Lafountain, K. Cohen and S. Abdallah, Use of XFOIL in design of camber-controlled morphing UAVs, *Computer Applications in Engineering Education*, doi: 10.1002/cae.20437, 2001.
8. A. Tomczyk, The flying laboratory for aeronautics students' education, *Aircraft Engineering and Aerospace Technology*, **82**(5), 2010, pp. 320–330.
9. B. J. Chartier and B. A. Gibson, Project-based learning: a search and rescue UAV—Perceptions of an undergraduate engineering design team: a preliminary study, *Proceedings of the 2007 Australasian Association for Engineering Education (AaeE) Conference*, Melbourne, Australia.
10. N. Amireh, P. Kang, D. Strom and C. K. Chui, Modular toy aircraft, *Patent US7811150B2*, 2010.
11. G. S. Sommer, Modular aircraft articulated-wing, *Patent US7789339B2*, 2010.
12. J. Roskam, *Aeroplane Design: Parts I–VIII*, DARCorporation, Lawrence, KS, 1997.
13. J. J. Bertin and R. M. Cummings, *Aerodynamics for Engineers*, 5th edn, Prentice Hall, New Jersey, 2008.
14. J. Katz and A. Plotkin, *Low-speed Aerodynamics: From Wing Theory to Panel Methods*, McGraw-Hill, Inc., New York, 1991.
15. J. Richards, A. Suleman, T. Aarons and R. Canfield, Multidisciplinary design for flight test of a scaled joined wing sensorcraft, *CSME Forum 2010*, Victoria, British Columbia, Canada, 2010.
16. Tornado vortex lattice method, http://www.redhammer.se/tornado/index.html, 2011.
17. Athena vortex lattice, http://web.mit.edu/drela/Public/web/avl, active in 2011.
18. C. Bovais, D. Levy, G. Page, S. Powell, M. S. Selig and T. Zickur, Writing the rules: an inside look at the AIAA student design/build/fly competition, *AIAA 6th Aviation Technology, Integration and Operations Conference (ATIO)*, AIAA Paper 2006–7832, Wichita, Kansas, 2006.
19. F. W. Lanchester, *Aerodonetics*, A. Constable & Co. Ltd, London, 1908.
20. S. Pradeep, A century of phugoid approximations, *Aircraft Design*, **1**(2), 1998, pp. 89–104.
21. R. Jategaonkar and W. Gruenhagen, Aerodynamic modeling and system identification from flight data—recent applications at DLR, *Journal of Aircraft*, **41**(4), 2004, pp. 681–691.
22. J. E. Williams and S. R.Vukelich, The USAF stability and control DATCOM, *Tech. Rep. McDonnell Douglas Astronautics Company*. AFFDL-TR-79-303, 1979.

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