How industry concepts of concurrent engineering enhance aircraft design education

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Abstract: Two student projects are described including the intended goals, the approaches taken, the tools used, and what was learned from the exercises. An international collaborative teaching protocol between Ecole Polytechnique de Montreal and the Royal Institute of Technology (KTH) was exercised in aircraft design education. Poignantly, a novel instructive design process using the analogue of contemporary concurrent engineering practices in industry was implemented. The idea was to strategically assign multi-disciplinary design tasks to each Partner University in accordance with their respective competencies. The university–industry coupling was initiated by request for proposals and corresponding marketing requirements and objectives produced by Bombardier Aerospace in Montreal, Canada. Two MATLAB™-based tools were prominent in facilitating the capstone aircraft design projects. They included: Quick Conceptual Aircraft Research and Design, a computer-aided conceptual design engineering system; and TORNADO, a Vortex-Lattice code for computing aerodynamic characteristics. The result of the two exercises was found to benefit the participating industry, the educational establishments involved, and the students carrying out the projects.

Keywords: aircraft, conceptual, design, education, aerodynamics, stability, control, flight, handling, simulation

1 INTRODUCTION

Today, the standard in many of the capstone aircraft design projects at universities and technical institutions is to focus on fostering teamwork in a multi-disciplinary design setting. Many educational institutions count on the involvement of industry in not only defining the nature of each project, but also in committing to some degree of participation, i.e. authorship of course notes, lectures, tutorials, attendance at meetings, marking, etc. One evolutionary direction in design education that has recently emerged is analogous to the modern era of aircraft product development where integrated product development teams (IPDT) of an aircraft integrator collaborate with suppliers or risk-sharing partners. This education programme can be best classified as a multi-party approach by which industry–university and university–university relationships are fostered, subsequently strengthened, even helping to generate previously non-existent third-party industry–university ties.

Present trends in aircraft design towards augmented-stability and expanded flight envelopes call for a more accurate description of the flight-dynamic behaviour of the aircraft in order to properly design the flight control system (FCS). Hence the need to increase the knowledge about stability and control (S&C) as early as possible in the aircraft development process in order to be 'First-time-right' with the

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FCS design architecture. Up to 80 per cent of the life-cycle cost of an aircraft is a direct result of decisions made in the conceptual design phase, and so mistakes must be avoided. The European air-transport sector has set the agenda in their second Advisory Council for Aeronautic Research in Europe 'Vision 2020' Report [**1**] SRA-2, where a number of goals for the environmental impact of air transportation have been itemized. An emerging view is that such ambitious targets will not be met without some element of innovation in the education of the future aerospace engineers who will be entering the workforce. A framework that supports state-of-the-art computer-aided concept designs suitable for procuring economically amenable and ecologically friendly designs is seen to be the priority. In the opinion of the authors, one aspect that would serve to deliver such important goals is the (architectural) discipline and (technical) subspace of S&C and thus subsequently emphasized in this treatise. To this end, it is essential to integrate appropriate software tools when it concerns the instruction of aircraft design and systems integration.

A relatively recent tool, Quick Conceptual Aircraft Research and Design QCARD [**2**], introduced in 2002 and currently undergoing an extensive enhancement phase, is the one the authors believe that combines the right mix of functionality when it concerns information technology, because it reflects a measure of contemporary industry practice. In addition, one fortuitous aspect is the fact that it is geared to cater for the student-level of ability. Traditionally, commercial aircraft conceptual design systems like Project Interactive Analysis and Optimization [**3**], Advanced Aircraft Analysis [**4**], and Raymee Design Software [**5**] make extensive use of the so-called handbook methods on the basis of parametric correlations and semi-empirical analytical constructs. More sophisticated and powerful versions of such conceptual design software platforms can be found in industry. These proprietary, in-house-developed systems are the result of experience accumulated from a series of previous design projects, which usually infuse a series of existing handbook methods.

A growing consensus of opinion, however, finds that these handbook methods and such comprehensive databases are not reliable enough for treating novel and unconventional designs, and thus, there is a trend towards replacing the methods with computational procedures that calculate the required information from first principles. As an example, QCARD includes, as a subsystem, the Vortex-Lattice Method (VLM) code TORNADO, a numerical aerodynamics software that employs the Vortex method Lattice [**6**], in order to compute the aerodynamic characteristics of a given design morphology. TORNADO, written in MATLAB™, allows the user to define most conceivable types of aircraft morphologies, with multiple wings, both cranked and twisted with multiple control surfaces. It currently generates the static and constant-rate stability derivatives; in an unsteady aerodynamics version to be released soon, even the dynamic derivatives [**7**] will be available for computation as well. The code has found many uses in the aeronautical design and educational community, and its continuous development has spawned new educational tools as well as new research possibilities [**8–10**].

It would be a misleading message if the instruction in design gives students the impression that systems architecture and integration are done with just concepts and software, reinforcing the notion that testing is a thing of the past. The aerospace community in general, therefore, has the obligation to embrace the rich synergy that comes through close coupling of simulation and numerical-physical testing. From the onset of controlled, manned flight up until the 1950s, testing was the predominant approach: the so-called 'cut-and-fly' approach to design. Today, it co-exists with simulation – both in terms of assessing concepts and confirming predicted performance. The authors do not dispute the idea that physical testing will always be the ultimate milestone in verifying a design concept – the only open question that remains is the extent at which economic and man-power outlay is to be rationalized.

This treatise describes two different types of student aircraft design projects that have been completed in aerospace systems and design integration courses offered at Ecole Polytechnique de Montreal (EPdM) in Canada, and the Royal Institute of Technology (KTH) in Sweden. The authors will provide examples that reflect issues discussed above in relation to the teaching of aircraft design, and the paper will conclude by offering some reflections on what was learned in the process.

2 THE QCARD COMPUTER-AIDED CONCEPTUAL DESIGN TOOL

In a broad sense, the entire aircraft design process can be categorized into three distinct phases:

(a) conceptual definition;
(b) preliminary definition;
(c) detailed definition.

Depending on the requirements of time and resources deemed appropriate by the airframe manufacturer, the conceptual definition phase itself cannot be branded as adhering to one type of mindset. In fact, as exemplified by Fig. 1, there exist two tiers under

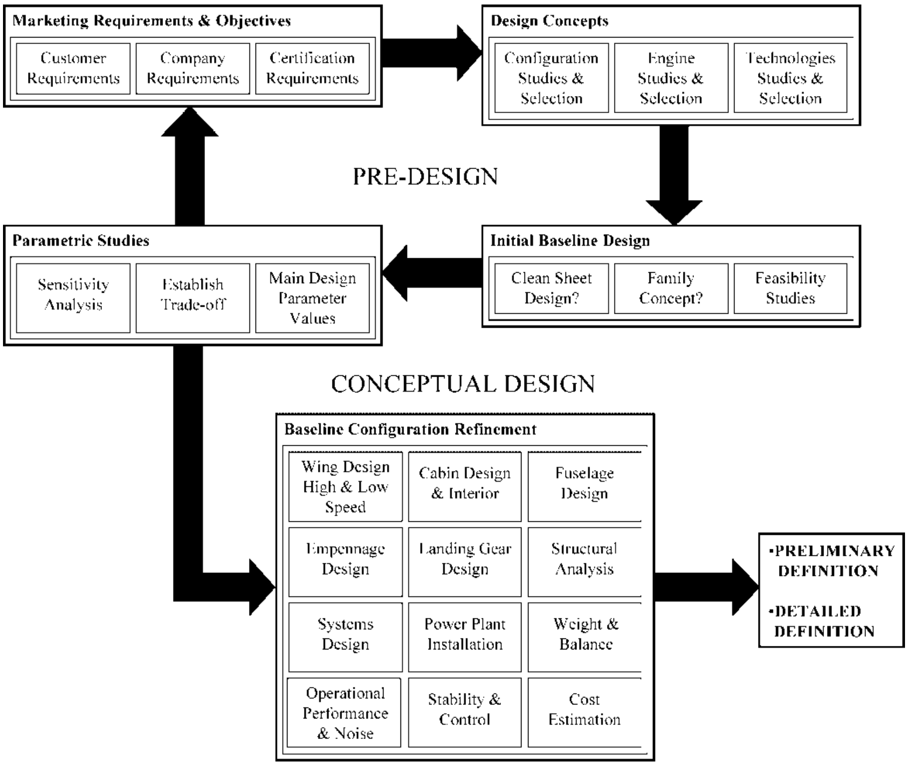

Fig. 1 Illustration of the conceptual design process segmented into two tiers: the initial or 'predesign' and refined baseline configuration definitions

this phase; one aimed at establishing a very quick (timescale can be from one to several weeks) yet technically consistent feasibility study, some call predesign and the other would be a protracted and labour intensive effort involving more advanced first-order or even higher-fidelity trade studies to produce a refinement in defining the minimum goals of a candidate project. During the preliminary definition, product design is still undergoing a somewhat fluid process and indeed warrants some element of generalist-type thinking. It can be thought of essentially as a constrained exercise because the minimum goals of the project have already been established during the conceptual definition phase and the aim is to meet these targets using methods that do not necessarily reflect the conventional wisdom established during the conceptual definition phase. Furthermore, the participants in this working group are mostly genuine specialists in each respective discipline. As the status of a project is well within the preliminary design phase, assuming the manufacturer has confidence in the potential for a new product line and has established a development cost it is willing to absorb, the detailed definition phase would begin after the project is formally launched.

QCARD [**2**] is an interactive MATLAB™-based conceptual design package, which allows the design of gas-turbine-powered transport aircraft (Fig. 2). The system functionality is specifically tailor-made to predict, visualize, and assist in optimizing

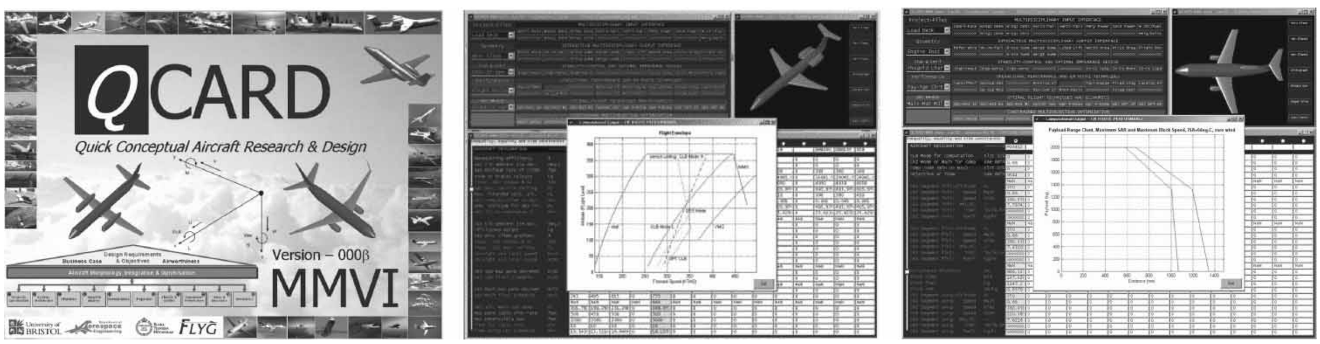

Fig. 2 Screen shots of QCARD computer-aided engineering system for aircraft conceptual design

conceptual aircraft designs with emphasis placed on user interactivity. Critical development objectives included acceleration of design response time with a significant increase in design freedom, conformity, and consistency of the results. Hidden and explicit Decision Support System functionality provides the user with a wide-ranging freedom in defining as many or as few independent variable quantities. A feature allowing preset or in-house-defined parametric associations, historical data, trend information, and analytical assessments are also available.

Through total user control, the designer can create, calculate, and analyse 15 configurationally and parametrically distinct designs concurrently. The package affords a systematic and transparent process to not only conduct analyses with respect to geometry construction, weights and balance, propulsion, aerodynamics, S&C (using the Mitchell [**11**] code), and integrated operational performance, but also facilitates coupling of the en route performance subspace to that of economic criteria as defined by direct operating cost and profit/return on investment. An option is also available to conduct hypo-dimensional constrained multi-objective optimization using evolution methods, the Nelder-Mead Simplex search or a cocktail of both.

Near-term plans include the coupling of three additional subspaces: structural topology, systems architecture definition, and community noise and emission prediction modules. Further development will involve the implementation of formalized trade-studies, uncertainty analysis concepts, and risk assessment toolkit for the purpose of assisting decision-making and promoting design robustness during the initial technical assessment (ITA) phase. In addition, to complement the aforementioned functionality, the economics module will be extended to permit quantification of life cycle cost and net present value. A final enhancement will be the development of an aircraft facsimile generation interface. This routine via manual-synchronization or auto-synchronization will generate calibration models of known aircraft using methods commensurate with the detail of dataset information available to the user.

2.1 Predicting high-speed and low-speed aerodynamics

Today, early indications are emerging that the aerospace sector is undergoing some changes with respect to how vehicles are designed, built, and operated. It appears that the analytical tools currently available for conceptual design engineers to conduct feasibility studies that 'push the envelope' in terms of minimizing development costs and creating shifts in operational paradigms are not suitable due to the predominant philosophy of simply utilizing and coding existing, sometimes outdated, handbook methods. Many new methodologies that approach the conceptual design problem from a different perspective are to be reviewed in this body of work. Together with the main focus of generating theories more compatible in applicability and scope for requirements stipulated by contemporary design offices, they are also devised expressly for the purpose of being utilized to investigate the more seriously contemplated concepts currently gathering momentum, such as highly synergized progenitor or family concepts, and high transonic and/or supersonic commercial flight.

The importance of predicting low-speed and high-speed aerodynamic qualities of aircraft cannot be understated. The implication to vehicular definition relates to an initial appreciation of how the flight envelope will look as well as being one of the integral components in formulating the aeroplane's operational performance attributes. The main aim is to develop methodologies, in which the designer has an ability to examine the design space in a more sophisticated manner, not only in terms of departing from the usual more simplified approach premise but on account of the impact a technological decision makes to the end result. These two primary goals must also be tempered by an appreciation for reduction in the analysis complexity. This is surmised as being achievable by first of all soliciting the designer's philosophical requirements and translating this notion into single all-encompassing algorithms that provide visibility to the designer. Secondly, the methodologies must be robust with respect to stoppage when key information required on the part of the designer is found to be lacking.

The TORNADO [**6**] code is a VLM, programmed to be used in conceptual aircraft design and in aerodynamics education. Work on the code began in 1999 at the Department of Aeronautics, KTH, Stockholm, Sweden. The first version was released in 2001 together with the users manual and code description. This work began as part of the Masters thesis of Melin [**12**], the code developer. A sample of the scope of results generated by the software is presented in Fig. 3.

The aircraft geometry in TORNADO is fully three-dimensional with a flexible, freestream following wake. TORNADO allows a user to define most types of contemporary aircraft designs with multiple wings, both cranked and twisted with multiple control surfaces located at the trailing edge. Each wing is permitted to have unique definitions of both camber and chord. The TORNADO solver, which computes forces and moments, provides the basis of quantifying associated aerodynamic coefficients. The aerodynamic derivatives can be calculated with respect to: angle of attack, angle of sideslip, roll-pitch-yaw rotations, and

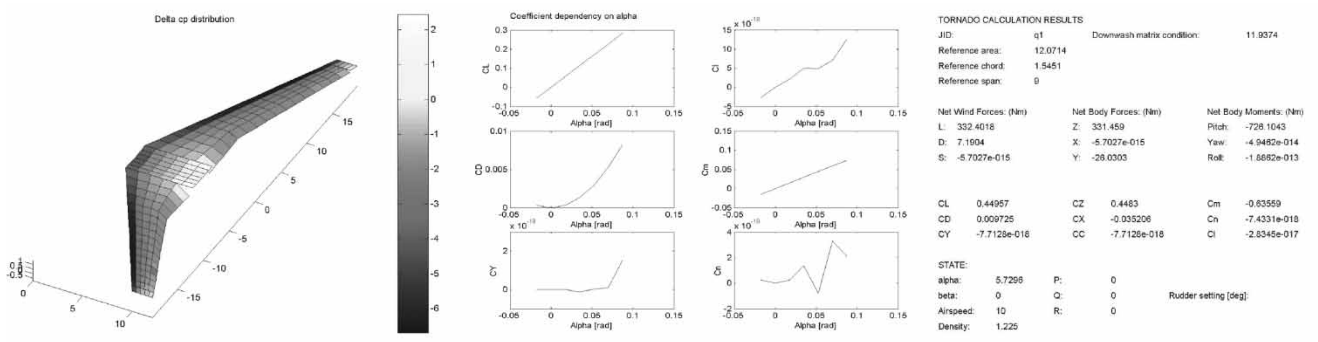

Fig. 3 Screen shots of the TORNADO numerical aerodynamics prediction software

discrete control surface deflection. If necessary, all of these conditions may be applied simultaneously. Any user may edit the program and design add-on tools as the program is coded in MATLAB^{TM}, and the source code is provided under the General Public Licence (http://www.gnu.org/copyleft/gpl.html).

The core method stems from Moran [**13**], but has been modified in order to accommodate a three-dimensional solution and discrete trailing-edge control surfaces. The most notable change is the extension of the theory of the horseshoe vortex into the vortex-sling concept. The vortex sling is essentially a seven-segment vortex line, which for each panel, starts at infinity behind the aircraft, reaches the trailing edge, moves upstream to the hinge line of the trailing-edge control surface, then forward to the quarter chord line of the panel in question, going across the panel, and then back downstream in an analogous way. The issue of the wake passing through the geometry at certain flight conditions is resolved by a collocation point proximity detection routine that automatically removes the influence from a vortex thread passing too close to a collocation point.

The code is generally distributed in the hope that it will be useful, but without any warranty; without even the implied warranty of merchantability or fitness for a particular purpose. However, validation comparisons have been conducted in which the code output is compared with actual data. The test case for the original steady aerodynamics version was the Cessna 172 – validation was conducted using Cessna Aircraft Company released flight test data [**14**]. The steady-TORNADO version was also benchmarked against computational results produced by Athena Vortex-Lattice (AVL) [**15**] and Panel Method Ames Research numerical aerodynamics softwares (Pmarc) [**16**], a VLM, and a panel method, respectively. A work-in-progress unsteady aerodynamics version of TORNADO has recently been validated using static and dynamic stability derivatives data for the Saab 105 (Fig. 4), which is an advanced air force trainer with reconnaissance and ground attack capabilities.

2.2 Stability and control analysis

Although all the other core disciplines are addressed with some element of detail during the conceptual design phase, one area of investigation that has traditionally lacked any form of sophisticated depth is S&C. Historical trend sizing of the empennage and

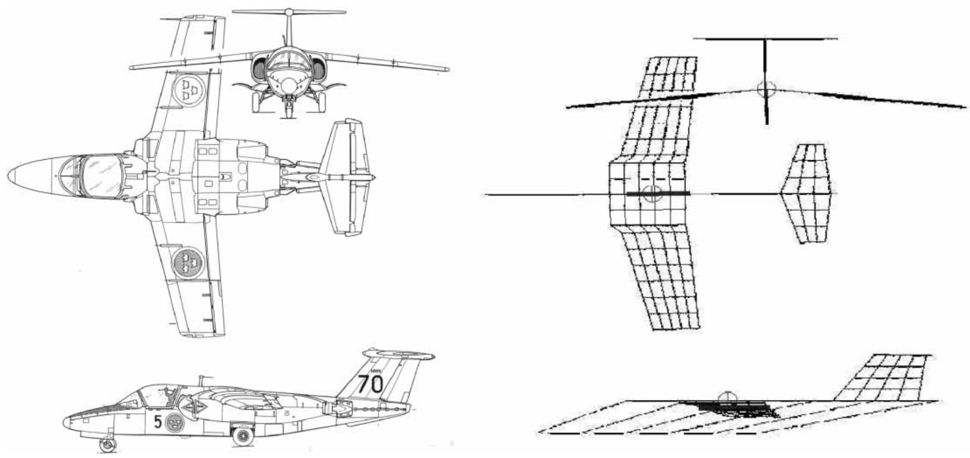

Fig. 4 Representation of Saab 105/SK-60 aircraft in TORNADO geometric domain

the control surfaces through a tail-volume approach [**16–18**] is usually deemed sufficient. This circumstance is quite puzzling considering the unavoidable fact as Cook [**19**] states while referring to the Wright Brothers: '. . .stability and control comprised the single most critical requirement for flight. . .'. Without question, most aircraft projects have experienced problems associated with vehicular flying qualities and pilot-in-the-loop response attributes, particularly those aircraft configured as powered (boosted), or otherwise, manual primary FCS. The difficulties in achieving satisfactory qualities become even more pronounced when the powered FCS needs to be complemented by some form of manual reversion as well.

When discussing the S&C attributes of an aircraft, two fundamental handling characteristics are cited as controllability and manoeuvrability. Controllability pertains to an attribute that enables the pilot to initiate and subsequently maintain a manoeuvre. The primary concern of controllability is establishing a vehicular reaction one would normally expect to a given stick command, and then extending that attribute to an assessment of the ease or difficulty in maintaining such an initiated manoeuvre. Manoeuvrability, alludes to the aptitude of a pilot–aircraft system to effect changes in the flight path, angular rates, and speed of the aircraft. Other concerns such as time lag, overshoots, and necessary compensation by the pilot during entry into a manoeuvre and maintenance of a steady-state acceleration, and return to normal flight come into consideration as well.

3 COLLABORATIVE STUDENT DESIGN PROJECT – HORIZON 1100

An international collaborative teaching approach to aircraft design education, begun in late-2003, comprised an industrial partner, Bombardier Aerospace located in Montreal, Canada and two educational institutions: EPdM based in Montreal, Canada and KTH in Stockholm, Sweden. The idea here was to assign multi-disciplinary design tasks to each partner strategically chosen in accordance with their respective competencies. The strengths of EPdM included world-class facilities for conducting virtual product integration and a curriculum that imbues a solid understanding of systems integration. KTH offers application of specialized knowledge and utilization of internationally recognized in-house-developed numerical tools giving an ability to address aspects relating to aircraft morphology, aerodynamic design, and refined sizing for S&C. The approach taken was inspired by the modem era of aircraft product development where IPDTs of an aircraft integrator collaborate with suppliers or risk-sharing partners (Fig. 5).

3.1 Teaching model based on concurrent engineering concept

Marketing requirements and objectives (MR&O) is a set of design specifications in industry, and in the undergraduates' design course, it is issued as a request for proposal (RFP) to the collaborating universities. The joint-technical-assessment phase in industry involves pooling together a select group of specialists and conceptual designers for a more detailed assessment. In the design courses, the Prime (EPdM) University's ITA is handed-off to the Collaborating (KTH) University for a subsequent, deeper study, hence, assuming the role as 'specialist'. The joint-conceptual-definition phase JCDP in industry involves potential suppliers and risk-sharing partners, along with the aircraft manufacturer's system integrators who further develop the basic system architecture and functionality. Once the milestone of closing out the collaborative aircraft design education is completed, lessons learned are cycled back to each of the universities involved.

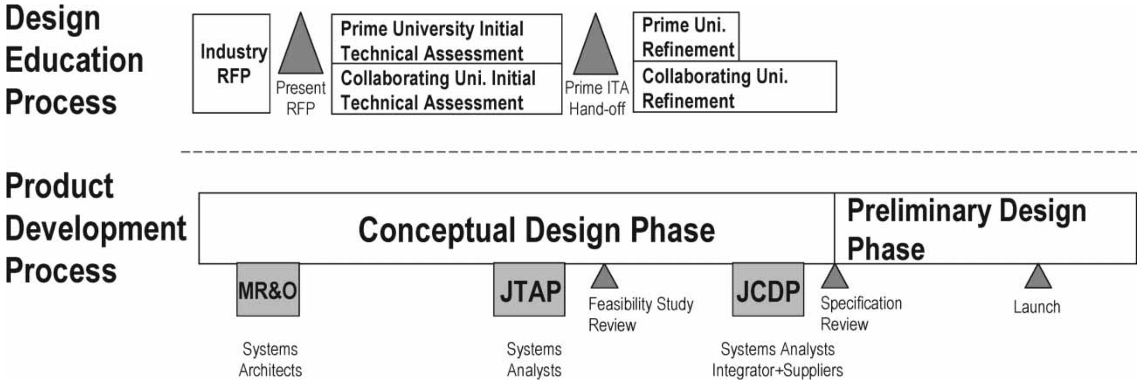

Fig. 5 An international collaborative teaching approach to aircraft design education using the IPDT-Integrator-Supplier analogy

The educational process begin with, for example, Bombardier Aerospace's Advanced Design Department producing an RFP document providing a brief overview of the target market – an exemplar cited for this paper is a next generation regional transport, and itemization of the MR&O, found in Table 1. In short, it called for a 50–70 passenger (PAX) family of regional transports focused on turboprop renewal and organic growth within the turbofan-engine fleet domain. A set of high-level specifications for the baseline aircraft are:

(a) 70 PAX at 31 in. (0.79 m) seat pitch;
(b) limited-scale operations such as thin routes, actual PAX loads fluctuate;
(c) combined exceptional field performance with high productivity;
(d) must fly in and out of London city or Toronto city centre (steep approach);
(e) Columbus–Denver city pair;
(f) must operate autonomously;
(g) emphasis placed on marketability (PAX preference).

The family member was stipulated to be a 50-PAX regional, and additional members could be missionized aircraft for freighter, corporate, and government/military usage.

Thereafter, EPdM with one inter-disciplinary team comprising 20 undergraduates proceeded with a 14-week conceptual design effort. Paralleling this, three KTH undergraduates over the course of 14 weeks investigated in more detail (although still at a conceptual design level) specialized aspects of the initial design generated by the EPdM team. A staggering of posted results and final documentation from each team occurred due to each institution's different timetables; KTH generally has additional time, and hence, conducted further refinements. As it can be discerned in Fig. 5, this process mimics the fashion in which technical task sequencing usually occurs in product development programme schedules – in the sense after the preconceptual design phase is completed, an increasingly more detailed (conceptual) ITA phase would be undertaken.

3.2 Market niche identification for next generation regional aircraft

The regional aircraft market comprising 70 PAX equipment types is quite attractive because regional aircraft are increasing in capacity with passing time. On the heels of the spectacular expansion witnessed for 50 PAX regional aircraft, airlines are now looking ahead to acquiring 70 PAX or larger equipment types in an effort to maintain a reasonable level of

Table 1 Bombardier aerospace's request for proposal and itemization of the marketing requirements and objectives for a next generation regional transport

	New regional transport
Accommodation	70 PAX
Seat pitch	At least 31 in. (0.79 m)
Weight per PAX	225 lb (102 kg) includes baggage
Baggage volume	At least 7.0 cu.ft (0.20 m^3) per PAX
Overhead bin volume	At least 2.0 cu.ft (0.06 m^3) per PAX
Design range, IFR, 100 nm alt.	1500 nm (2780 km) at M0.70
Out-and-return maximum range	At least 800 nm (1485 km) at M0.70
Number of 200 nm sectors without refuelling	At least 4
Long range cruise	At least M0.65
Normal cruise	At least M0.70
Maximum cruise	At least M0.75
Takeoff field length, ISA, s.l.	<4200 ft (<1280 m)
Takeoff field length, ISA + 30 °C, 5000 ft	<6500 ft (<1980 m)
Approach speed	<120 KCAS
Initial cruise altitude, ISA, MTOW at takeoff	At least 31 000 ft
Time-to-climb, ISA, MTOW at takeoff	<25 min
Single engine net ceiling, ISA, 95% MTOW	At least 17 000 ft
Service ceiling	At least 35 000 ft
Service life	80 000 cycles
Fatigue life	200 000 cycles
Operational requirements	High elevation airports unpaved and contaminated runways design intent for steep-approach 99.0% dispatch reliability and 99.5% scheduled completion rate at EIS RVSM
Emissions	CAEP6 with 40% margin for NO_X, CO, Hydrocarbons, and Smoke
Noise	Average for cabin 76 dBA
	Stages 4–20 EPNdB
Operating economics	Cash operating cost at least neutral with best comparable turboprop

revenue growth and protection of margin. Moreover, one entire generation of old regional turboprop aircraft will be replaced soon. These aircraft are known by airliners for their superior low-speed climb capabilities and exceptional field performance. Although a healthy strong migration to faster turbofans has occurred for the last several years, prohibitively high-fuel consumption of these aircraft now mitigates their economical efficiency.

The market served by the AeroX Horizon 1100 expects a low trip cost and equivalent low-speed performance of turboprops (field performance, initial climb capabilities) with an increase in cruise speed and range, characteristics that cause the airlines to migrate from turboprops to turbofans. These advantages are posited to open new routes and increase the efficiency of feeding major hubs. The objective of the design was also to offer a standard comfort to passengers with an acquisition price that falls in the middle of turboprops and turbofans of the same category.

3.3 Ecole polytechnique de Montreal initial design

The AeroX Horizon 1100 (Fig. 6) was EPdM undergraduates' initial baseline design [**20**] – a regional, commercial, low operational cost aircraft that offers very competitive attributes in terms of field performance, fuel burn, range, and speed. It represents the best compromise for replacement of soon-to-be-obsolete turboprop aircraft and high cost to operate turbofan aircraft.

Horizon 1100 has a low-wing morphology, with two aft fuselage-mounted GE-38 unducted-fan engines and comprises double-wheeled, retractable landing gears in a tricycle layout. Its double-bubble fuselage is specifically designed to store the baggage under the floor and equipment in the tail cone. It has wing slats and single slotted Fowler flaps with engine pylons acting also as stabilons, and a T-tail to provide the best control particularly during low-speed trim and manoeuvres.

3.4 The royal institute of technology technical assessment

The KTH undergraduates were petitioned to provide an aerodynamic and flight mechanics analysis [**21**] of the EPdM initial baseline. Their analysis looked at the suitability of the chosen aerofoil for the cruise speeds outlined in the MR&O, and ascertained compatibility for meeting additional requirements of good short-field performance so that the aeroplane can additionally perform the traditional roles of turboprop, i.e. servicing smaller secondary airports.

Having received the final layout of the aeroplane from the project partners at the EPdM, the KTH undergraduates performed an S&C analysis of the proposal using QCARD. In turn, changes were made to the dimensions of the aerodynamic surfaces and to their position with respect to the fuselage in order to conform to minimum requirements dictated by handling qualities.

3.4.1 High-speed and low-speed aerodynamics assessment

The Horizon 1100 is planned to cruise at an altitude of 35 000 ft (10 670 m) at Mach numbers between $M_{\text{LRC}} = 0.65$ (long-range cruise) and $M_{\text{MCRZ}} = 0.75$ (maximum cruise speed); the normal or standard operational cruise Mach number being $M_{\text{STD}} = 0.70$. At such low- to mid-transonic speeds, the compressibility effects cannot be neglected, and thus, a high-speed study of the aerodynamics of the wing was deemed necessary. Indeed, it was appreciated upfront that a

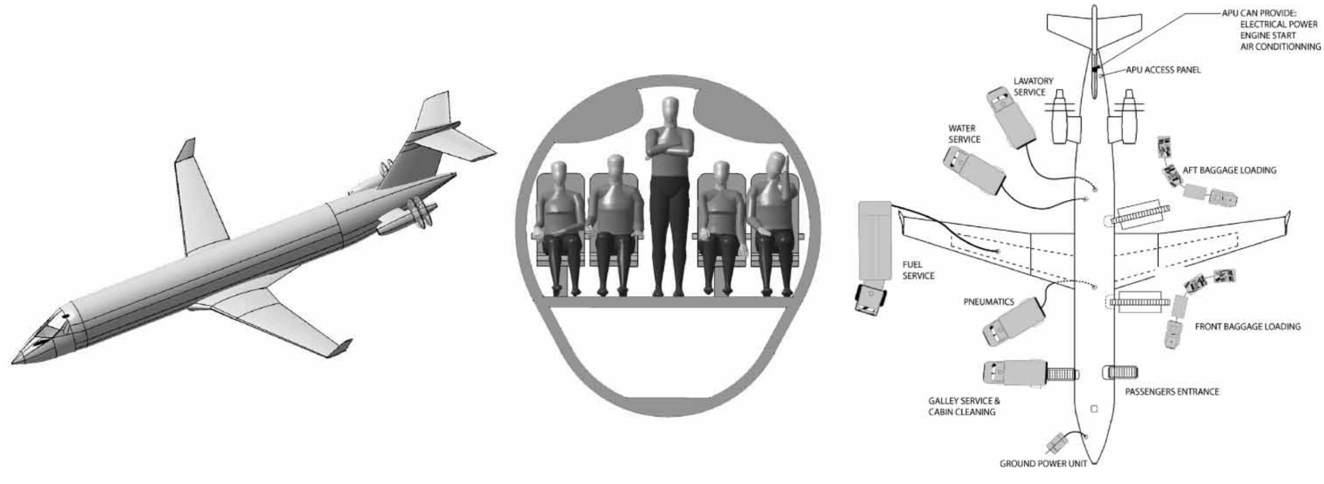

Fig. 6 AeroX Horizon 1100 is a regional low operational cost aircraft with two aft fuselage-mounted GE-38 unducted-fan engines

better notion of the penalizing aspects imparted by compressibility effects or the wave drag component needs to be gained. At the low- to mid-transonic speed regime, wave drag is considered as being attributable to shock waves appearing over the wing surface due to localized super-velocities.

For the purpose of examining high-speed aerodynamic performance, the MSES (numerical aerodynamics software that employs a coupled viscous/ inviscfd Euler method) [**22**] code was used. There are several ways to reduce and delay the drag rise due to shock formation on the wing. The most dramatic approach is achieved by selecting an appropriate aerofoil profile, followed by sweeping the wing, and finally by tuning the wing geometry by adjusting the twist distribution. The EPdM baseline design used the supercritical airfoil MS(1)-0313 [**23**], and the main wing had a quarter-chord sweep of 17.6°.

3.4.1.1 Two-dimensional analysis. Initially, a two-dimensional analysis of the selected wing profile MS(1)-0313 had been done using simple sweep theory [**24**] combined with results produced by the MSES code. The variation of the drag coefficient (C_d for two-dimensional and C_D for three-dimensional) with increasing Mach number for different lift coefficients is presented in Fig. 7. This figure shows a sudden rise in the C_d when the wing enters the transonic regime. Up to approximately $M = 0.60$, the C_d appears somewhat constant since it increases very slowly. As M becomes larger, it increases at a geometric rate due to the wave drag effects. When it comes to aerodynamic tailoring, there exist two relevant speeds: the so-called critical Mach number (M_{cr} for two-dimensional and M_{CRIT} for three-dimensional) and the drag divergence Mach number (M_{dd} for two-dimensional and M_{DD} for three-dimensional). M_{cr} is the M when supersonic flow is first encountered over the wing profile. M_{dd} is the M at which a pronounced divergence of drag takes place – it is generally defined to be the M when the C_d value is 0.0020 (20 counts) higher than the drag coefficient at M_{cr}. Figure 7, displays the values for both Mach numbers and corresponding operating lift coefficient (C_l for two-dimensional and C_L for three-dimensional). Upon inspection of Fig. 7, one can conclude there are preliminary indications that the wing of Horizon 1100 will fulfil the high-speed design requirements. The M_{dd} is always higher than the M_{MCRZ} and is always at least 0.15 higher than the M_{cr}, i.e. in a three-dimensional sense it is $M_{DD} - M_{CR} \geqslant 0.15$.

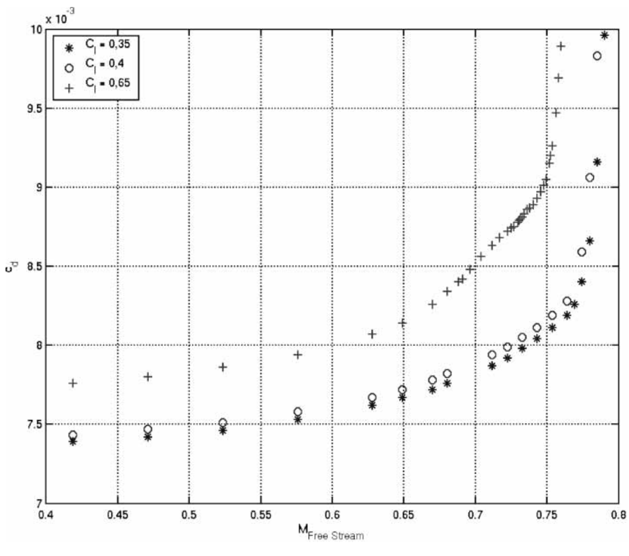

Fig. 7 Predicted drag coefficient versus Mach number for the Horizon 1100 regional transport computed with MSES for different constant lift coefficients

3.4.1.2 Three-dimensional study: TORNADO code. The aim of this part of the analysis was to determine the speed at which the aeroplane achieves the requisite lift for take-off. The maximum take-off weight (MTOW) of the aeroplane is 28 350 kg (62 500 lb). During the take-off roll phase TORNADO calculations indicate that enough lift will not be attained until an airspeed of 164 Knots, Calibrated Air Speed (KCAS) (84.0 m/s) is reached. At first glance, this speed was considered to be quite high, but of course it does not take into account the pilot, will rotate at a lower speed, thereby significantly increasing the operating C_L. Rotating to an angle of 13.5° is close to the stall angle of 14° but shows that take-off is possible from a minimum of about 105 KCAS (54.0 m/s).

One of the requirements for this aeroplane is the ability to perform steep approach operations as required at certain airports, e.g. London City Airport. To achieve the lift required to maintain a constant rate of descent (with a constant airspeed of 115 KCAS or 59.0 m/s), an angle of attack of 7.6° is required according to TORNADO results.

3.4.2 Stability and control assessment

One important task for the KTH students was to investigate the S&C attributes of the Horizon 1100 aeroplane. Such an analysis is most relevant, especially for a new design such as the one discussed in this treatise. An aeroplane in a steady flight condition constantly faces many disturbances, and to predict how the aeroplane will behave and how its controllability is affected is absolutely necessary. With this in mind, the KTH undergraduates used QCARD to predict moments of inertia, aerodynamic coefficients, and the stability modes of motion. QCARD is constructed to predict and visualize the stability modes, and together with TORNADO, is able to calculate other mechanical and aerodynamic properties of an aeroplane.

Using QCARD, the stability modes of the initial baseline design generated by the EPdM undergraduates were examined. It is highlighted that EPdM undergraduates employed the traditional, so-called volume coefficient method for sizing the empennage; examples of such an approach can be found in references [**18**] and [**25**] to [**27**]. By studying these results they concluded that the aeroplane had poor S&C and flight handling qualities (FHQ). In particular, the short-period and Dutch-roll modes proved to be quite unsatisfactory. As a result of this circumstance, significant improvements had to be made in order to ameliorate these problems and to keep within the frame of acceptable manoeuvrability and controllability.

3.4.2.1 Improved configuration design. As it will be motivated in the next sections, the initial EPdM-generated geometry was found to be unsatisfactory and the KTH undergraduates took it upon themselves to do an array of geometrical modifications. Initially, the main wing was moved forward; its reference area (S_W) was increased; and its aspect ratio (AR) and dihedral (Γ) were reduced. In addition, the horizontal tail had its area, S_{HT}, and AR, AR_{HT}, increased. Finally, the area of the vertical tail (S_{VT}) was reduced, due to the forward shift of the wing that tended to increase the tail moment arm. Figure 8 illustrates the differences between original and refined sizing for Horizon 1100.

On the basis of the aforementioned resizing of the wing and empennage, the undergraduates then proceeded to calculate the static aerodynamic derivatives, and subsequent to this, predicted all five modes of motion (Table 2 for results of Horizon 1100 original and refined sizing). They found that the refined configuration produced better drag properties and slightly less available lift – poignantly though, a more benign longitudinal static stability derivative, $C_{M\alpha}$, was predicted. Their trade thus gained improved longitudinal static stability characteristics at the expense of some loss in available lift.

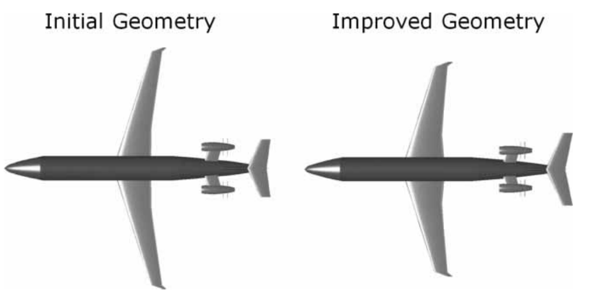

Fig. 8 Comparison of sizing for stability and control conducted by Ecole Polytechnique de Montreal (left) using volume coefficients and KTH (right) using semi-empirical analysis for static derivatives

3.4.2.2 Short-period stability mode. Most of the S&C problems of the initial geometry were associated with the Short-period longitudinal mode. The qualities of this mode when the aeroplane is in a standard cruise condition are presented in Table 2. The improved geometry has a shorter period and, more importantly, a shorter time-to-half, which is one key characteristic when attempting to fulfil the FHQ criterion. The collective impact of the improvements can be clearly understood upon inspection of Fig. 9, where the results concerning the Short-period mode have been plotted in an Engineering Science data unit (ESDU) opinion-contour graph [**28**] and using a Cooper–Harper rating scale for all cruise conditions ($M = 0.65, 0.70, 0.75$ at 35 000 ft).

Figure 9 shows that the initial geometry had a very poor rating – bordering on unacceptable FHQ. Although the FHQ improve with increasing M, they are still categorized as poor. In fact, it appears that the aircraft has a sufficient level of damping ratio, but the natural frequencies are too small, a direct result of the period- being too long. As a consequence, the response of the aeroplane would prove to be very sluggish and an excessive amount of pilot invoked compensation would be required. The conclusion one would draw from the opinion plot is that a large control-fed motion is needed to handle the aeroplane satisfactorily, thus inferring the vehicle would be quite difficult to trim.

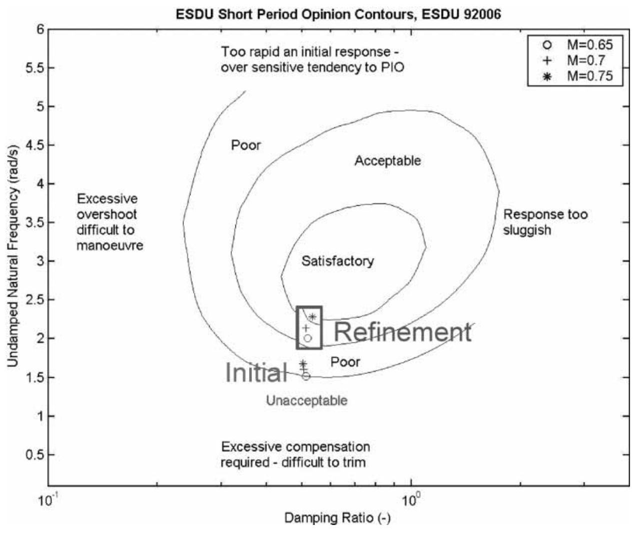

Fig. 9 ESDU [**28**] evaluation of the short-period characteristics for the Ecole Polytechnique de Montreal baseline configuration and the KTH refined configuration

To remedy this problem, the main wing was shifted forward while S_W was increased, and AR decreased. In consort, the horizontal tail S_{HT} and AR_{HT} were increased. As it is evident in Fig. 9, the improved geometry still has quite a good damping ratio of 0.52, however, the natural frequencies have now become high enough (the period has been reduced, Table 2). Thus, the aeroplane still has a relatively slow response but its FHQ can now be considered to be acceptable – even rated as satisfactory for the highest M. Notice that, as for the initial geometry, the FHQ improves with increasing M.

3.4.2.3 Dutch-roll stability mode. An irritable level of Dutch-roll motion is a common problem encountered by many swept-wing aeroplanes. It is particularly exacerbated when the aeroplane has an over-prescribed level of lateral stability. Table 2 gives the characteristics of the Dutch-roll and Fig. 10 compares them to military specifications (MIL-spec) [**29**, **30**] requirements. As can be observed in Fig. 10, the Dutch-roll characteristics of the initial geometry are not satisfactory since the damping ratio is too low. This is due to the excessive lateral stability of the initial design that leads the aeroplane to overshoot its equilibrium position by a large margin during the Dutch-roll oscillatory motion. To reduce the level of lateral stability, and thus cure the Dutch-roll problem, the main wing Γ and the vertical tail S_{VT} were reduced – it resulted in an improved geometry with a much higher damping ratio. Most noteworthy, the array of geometrical modifications did not affect the value of the Dutch-roll period much; Fig. 10 indicates that the improved geometry meets minimum FHQ requirements.

3.4.2.4 Limiting speeds. To conclude the S&C analysis of the initial and improved designs, prediction of the limiting speeds for dynamic motion of the Horizon 1100 was deemed important. The limiting speed is the speed at which one of the longitudinal or lateral modes of the aeroplane first becomes unstable. For both initial and improved geometry, it was observed that the spiral mode first becomes unstable and it occurs at speeds:

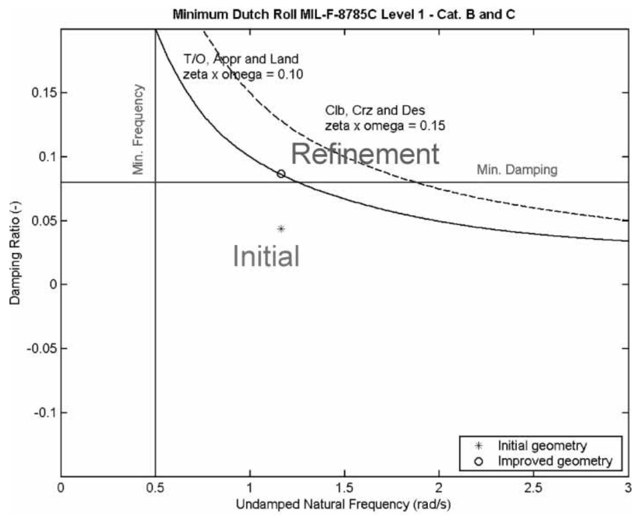

Fig. 10 Dutch-roll characteristics for the Ecole Polytechnique de Montreal baseline configuration and the KTH refined configuration superposed with MIL-spec [**27**, **28**] evaluation levels

(a) 136.5 m/s ($M = 0.440$) for the initial design;
(b) 141.5 m/s ($M = 0.455$) for the improved design.

The initial design remains stable at slightly lower speeds than the improved one but the difference is negligible. Moreover, such low speeds should never be reached in cruise conditions (35 000 ft); and even if the spiral mode becomes unstable, it has a quite large time constant (period), which gives the pilot time to counteract any trajectory deviance. In fact, those results bow to the evidence that both geometries of the Horizon 1100 have a very large safety margin before becoming unstable in the cruise condition.

3.4.3 Lessons learned

During this project, two cycles of conceptual design were completed. First, starting from an initial geometry suggested by the undergraduates of EPdM in their aircraft design project, an enhanced study of the aerodynamics of the wing, followed by an S&C analysis of the design of the full aeroplane was performed. The S&C analysis highlighted that some aspects of the longitudinal and lateral FHQ of the Horizon 1100 initial

Table 2 Characteristics of the longitudinal and the lateral modes during standard cruise ($M = 0.70$, 35 000 ft); computed with QCARD

Type of motion	Name	Period (s)		Time-to-half (s)		Cycles-to-half	
		Initial	Imprd	Initial	Imprd	Initial	Imprd
Longitudinal	Phugoid	>120	>120	94.98	95.9	≪1	≪1
	Short-period	4.35	2.92	0.82	0.58	0.19	0.20
Lateral	Dutch-roll	5.11	5.40	12.94	6.84	2.52	1.26
	Spiral	128.4	117.5	NA	NA	NA	NA
	Rolling convergenc	0.86	0.89	NA	NA	NA	NA

sizing were not acceptable. On the basis of a greater level of detail, although still with simplified analysis techniques, an improved geometry was identified with satisfactory FHQ.

Although the alternative wing suggested by the KTH team provided satisfactory FHQ, a trade-off in terms of higher fuel consumption due to increased drag (not considering the more benign wave drag) did result. Insofar as landing approach, the low wing AR alternative proved to be advantageous with its significantly higher drag. Notwithstanding this outcome, neither wing alone produces enough drag for steep approach operations and hence necessitates the incorporation of additional spoilers or dedicated airbrakes. Concerning the notion of high-speed aerodynamics, the choice of the supercritical aerofoil section MS(1)-0313 was found to be a satisfactory one since it fulfils good design practice of $M_{DD} - M_{CR} \geqslant 0.15$. Combined with the fact that M_{DD} is always higher than M_{MCRZ} means, the drag rise behaviour was therefore considered to be sufficiently benign in any cruise condition.

During the S&C analysis, it appeared that the longitudinal short-period and the lateral Dutch-roll modes of motion of the initial geometry were sources of concern. Indeed, the inherent characteristics of the aeroplane for these two modes meant that there was a likelihood that FHQ would be below minimum acceptable levels. This circumstance warranted some modifications to the geometry, leading to an improvement to the characteristics of the aeroplane for these two modes (short-period and Dutch-roll) whilet preserving the desirable characteristics of the longitudinal Phugoid and lateral spiral and rolling convergence modes.

In conclusion, starting from a geometry that had satisfactory aerodynamic characteristics but unacceptable S&C features, an improved geometry has been found that satisfies qualities for both aerodynamics and S&C.

4 INSTRUCTION IN FLIGHT-CONTROL: WRIGHT GLIDER REVISITED

The second student project carried out at KTH was quite different from the Horizon 1100 project in a number of ways: it was not conducted as a collaborative exercise outside of KTH, and was not an aircraft design project *per se*. Instead the aim was to aid in teaching the various elements of S&C of aircraft. In order for the undergraduates to carry out the FHQ analysis of the Horizon 1100, and to improve upon it, they needed a sufficient understanding of flight dynamics and acquire a new proficiency in making an application of it. In teaching and guiding undergraduates to reach this level of proficiency, several difficulties were observed – all having to do with the degree of abstraction of the subject matter. For example, given some numerical values for the aerodynamic static derivatives, they were asked to surmise how these values, once inserted into the equations governing dynamic flight would translate into influence on certain flight trajectories and associated FHQ. If this process could be made more concrete, the supposition was that the teaching, and thus the understanding of S&C would be markedly improved.

The approach that was finally employed drew off the synergy of combining MATLAB™ with an already developed SIMULINK simulation tool together with some simple wind tunnel testing. The intention was to retrace the steps of the Wright brothers because after all they were the ones who first solved the problem of pragmatic controlled flight without the benefit of the theory of flight dynamics, and in essence, were the progenitors of modern flight control. Others have taken a similar approach, for example Padfield and Lawrence [**31**] extensively investigated the Wright Gliders and corresponding control (Fig. 11). The reader is referred to Culick [**32**] for an interesting overall account of what the Wrights learned.

In 1903, Orville and Wilbur Wright performed the first controlled flight of a powered aircraft with the 1903 Wright Flyer. The progress to obtain the flyer was over a long timeline and the Wright Brothers built several kites and gliders before they understood the necessary aerodynamics to build their powered flyer. Prior to the 1903 Wright Flyer, the Wright brothers

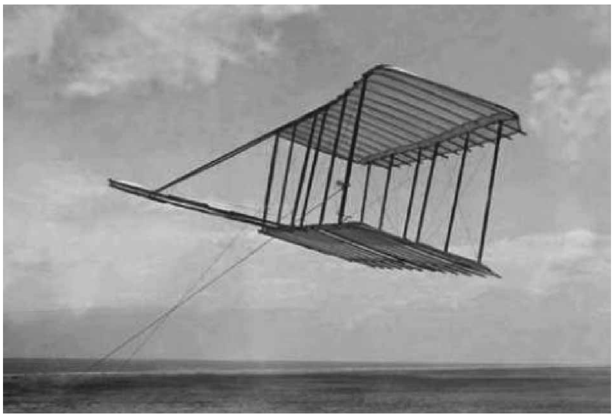

Fig. 11 The Wright brothers flight tested their glider with the unconventional forward elevator as a tethered kite in Kitty Hawk in 1900. It was here they discovered the rudimentary elements of stability and control

constructed the 1902 Wright Glider (Fig. 12), which was the first vehicle with a three-dimensional control capability and one that addressed the problem of flight control.

One is immediately drawn to the question: how did they reach this accomplishment? Already in 1899, they focused on solving the problem of lateral control by the pilot 'warping' the wing, and they tested it on a 5.0 ft (1.52 m) biplane kite. Confident their design was sound, in 1900 the Wrights built a 17.0 ft (5.18 m) glider with an unusual forward elevator (or canard). They went to Kitty Hawk hoping to gain flying experience, but the wings generated less lift than expected, so they flew the glider mostly as a kite, working the control surfaces from the ground. Figure 11 is a photograph of the glider configured for tethered flight in 1900. The results of these tests convinced the Wrights that they had achieved a sufficient level of longitudinal as well as lateral control. Over the course of 1901, they improved the lift of their glider and demonstrated that it was possible to control gliders in two spatial dimensions, namely, pitch and roll. Irrespective of this achievement, the machine still proved to be somewhat unpredictable: when the pilot raised the left wing to initiate an expected right turn, the vehicle instead tended to slip to the left (adverse yaw). Drawing on all their research, the Wright brothers altered the 1902 vehicle with more lift-efficient 32.0 ft (9.75 m) wings, incorporated a vertical tail including a movable rudder linked to the warping mechanism, and as a consequence, found it was also possible to control the yaw of the glider so that it could be turned and stabilized smoothly. Six hundred glides that year satisfied them that they had the first working airplane (Fig. 12). In a classic example of the 'cut-and-fly' approach during those 600 glides, they determined the requisite size of the vertical tail.

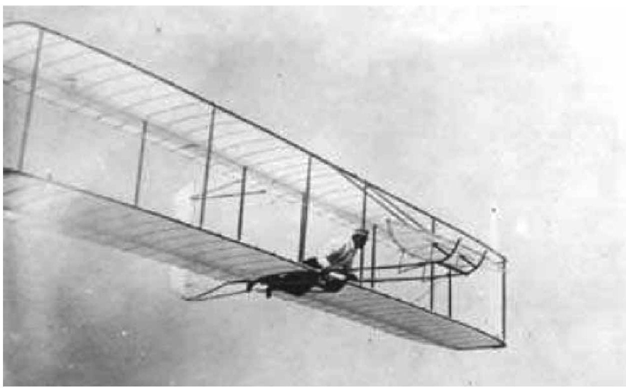

Fig. 12 The 1902 Wright Glider, the machine that solved the problem of flight control

4.1 Student assignment definition

The assignment given to the students then is, for stick-fixed conditions only, use wind tunnel testing together with simulation to determine the size of the vertical tail that gives acceptable yaw stability to the tethered 1902 Glider. In particular, begin with the initial (given) tail size and carry out the following actions.

1. Try first to obtain a stable and trimmed condition for the Glider with initial vertical tail tethered in the wind tunnel. Confirm this motion with KiteSim [**33**]. You will observe in both cases that the Glider is unstable in yaw.
2. Use KiteSim to determine how much additional authority is needed from the vertical tail to achieve stability. Use TORNADO to determine the size of a new tail that gives this authority.
3. Verify in wind tunnel that Glider with new tail is in fact stable. Compare the measured and computed trajectories.
4. Draw conclusions.

4.2 Wind tunnel model

A wind tunnel model of the 1902 Wright Glider was built for low-speed wind tunnel tests conducted in a tunnel with the cross-sectional size of 300 $\times$ 600 mm at the test section. This is a tunnel for student use and is much smaller than the one used in, for example, reference [**34**]. The model of the glider was built with a wingspan of 150 mm in order to avoid any interference from the wind tunnel walls, and therefore, ensuring a suitable account of finite wing effects. As the real glider has a wingspan of 9.75 m, the wind tunnel model was therefore built to a 1/64 length scale. The wind tunnel model was a simplification of the glider as only the main components were considered in the construction. The model consisted of the wings, the struts, and the skids only. Figure 13 shows the computer-aided design (CAD) description of the wind tunnel model.

4.2.1 Measurement system

The wind tunnel test results were analysed with the MATLAB^{TM} program DoTrack [**35**]. The tests were recorded with a camera that was mounted on top of the wind tunnel. The video clips obtained from the wind tunnel tests were analysed with DoTrack in order to deduce the motion of the model. DoTrack analyses each frame captured by the camera and detects bright spots painted on the model, positioned and numbered as shown in Fig. 14.

If the relative distance between the bright spots are known and defined in the program, the relative motion of the bright spots can be calculated from one

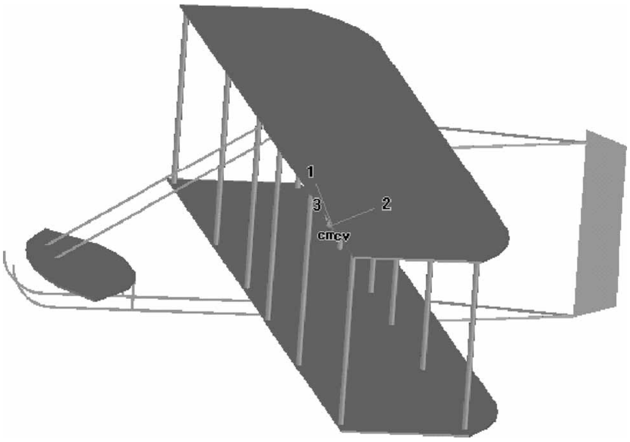

Fig. 13 Solid-edge CAD description of the wind tunnel model of the 1902 Glider used to calculate its moments of inertia

frame to another. Hence, the motion and attitude of the model can be determined. To highlight the bright spots on each frame, the wind tunnel background was darkened with a black sheet and the model was painted matte black.

4.3 Flight-dynamic model: KiteSim

A dynamic simulation, using a SIMULINK-based program called KiteSim, was carried out in order to examine the flying qualities of the tethered 1902 Glider. The flight dynamics model was set up in MATLAB™ SIMULINK with AEROSIM, an aeronautical simulation BLOCKSET v1.1 [**36**]. This information was useful in understanding how the Wright Brothers' subsequent designs evolved as a result of their test program. For the simulations in KiteSim, an aerodynamic database of the 1902 Wright Glider was required. The database included the following constituent information:

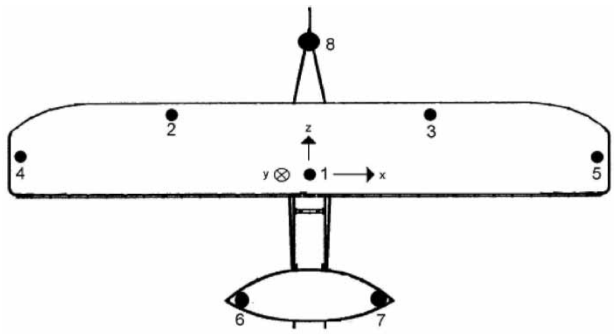

Fig. 14 Placement of eight dots on the wind-tunnel model that the optical measurement system DoTrack [**35**] uses to determine the model's position and orientation in space as if moving in time

(a) aerodynamic static derivatives computed with TORNADO;
(b) drag data, estimated using suitably calibrated, standard conceptual design semi-empirical algorithms;
(c) moments of inertia calculated about the centre of gravity from the Solid-Edge CAD model.

KiteSim employs a linearized aerodynamics model similar to LaRCsim [**37**], where for instance the linearized C_{L} is expressed in equation (1)

$$C_{\mathrm{L}} = C_{\mathrm{Lo}} + C_{\mathrm{L}\alpha}\alpha + C_{\mathrm{L}\beta}\beta + C_{\mathrm{Lp}}p + C_{\mathrm{Lq}}q + C_{\mathrm{Lr}}r \quad (1)$$

where C_{Lo} is the initial operating lift coefficient, $C_{\mathrm{L}\alpha}$ the aeroplane lift-curve slope, a the angle of attack, $C_{\mathrm{L}\beta}$ the rolling moment due to side-slip (the so-called dihedral effect), β the angle of vehicular side-slip, C_{Lp} the so-called dumping-in-roll derivative (resistance of vehicle to rolling motion) with roll rate, p, C_{Lq} the rolling moment due to pitching motion (q), C_{Lr} the rolling moment due to yawing motion, and r the yaw rate. The SIMULINK model implements a full set of equations of motion for a rigid body aircraft.

The total drag, C_{D}, was simplified to a standardized polar behaviour, according to equation (2)

$$C_{\mathrm{D}} = C_{\mathrm{Do}} + KC_{\mathrm{L}}^2 = C_{\mathrm{Do}} + \frac{C_{\mathrm{L}}^2}{\pi e \mathrm{AR}} \quad (2)$$

where C_{Do} is the zero-lift drag and e is the Oswald efficiency parameter.

The tether line was modelled as a simply damped spring system. Although this model would accept compression loads only, tension loads were observed in the simulations to follow. According to equation (3), the magnitude of the force, $\bar{F}_{\mathrm{t}}$, was linearly proportional to the line elongation, ε, and to the deformation speed, $\dot{\varepsilon}$, of the tether

$$\bar{F}_{\mathrm{t}} = k_1\varepsilon + k_2\dot{\varepsilon} \quad (3)$$

k_1 and k_2 are constants of proportionality.

The force transmitted by the line connected to the Glider was taken to be analogous to the propulsion hub of the kite. This implies that the line force is considered as a propulsion force, acting for a standard aircraft in what would be the propeller hub, and in the direction of the kite tether. The aerodynamic loads on the tether were neglected as the total drag force on the line was about four orders of magnitude lower than the loads on the kite.

4.3.1 *Aerodynamic derivatives, drag, and inertias*

A model of the 1902 Wright Glider was created in TORNADO, from which the aerodynamic coefficients and static derivatives could be calculated. The wings

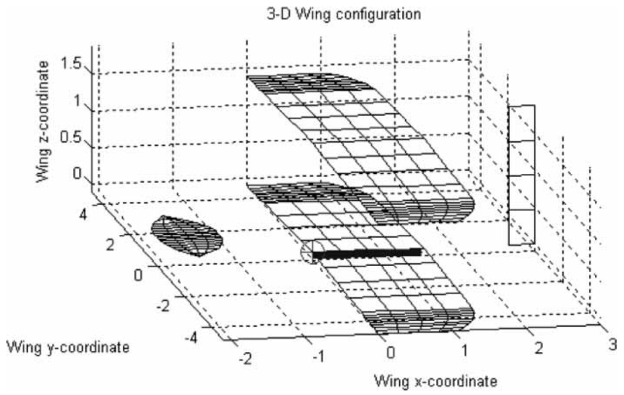

Fig. 15 Panelling in the TORNADO geometric domain of the 1902 Glider used for the computation of the aerodynamic derivatives

were taken as thin plates, and the struts, skids, and wires were neglected. Thus, only the main wings, the stabilizer, and the vertical tail are represented, although for reasons of numerical stability, the tail had to be simplified to a quadrilateral plate. Figure 15 presents the TORNADO representation of the 1902 Glider.

The aerodynamic coefficient dependency on α, β, p, q, and r were computed by TORNADO, and from these results, it was possible to estimate the aerodynamic derivatives required for the KiteSim simulations.

The drag estimate required values for the minimum drag condition, the lift at minimum drag, and e. In order to simplify the drag data calculations, some simplifications of the glider were made. To begin with, the glider was divided into these main components: the main wings, the stabilizer, the tail, and the struts between the main wings. A component build-up approach was subsequently performed. This simplification was done in order to avoid any interaction between the components, which would unduly complicate the analysis. The lifting surfaces were simplified as flat rectangular plates congruous with the original surfaces in terms of planform lengths and area. Furthermore, in the analysis, the struts were simplified as infinitely long circular cylinders. As the wings of the glider were assumed to be flat symmetric plates, the minimum drag could be assumed to occur at $\alpha = 0$. For the wings, the friction drag coefficient on each side of the plate was calculated with the Blasius relation [**38**]. Hence, the total drag at a velocity of $V = 10\,\text{m/s}$ was estimated to be $D = 50.6\,\text{N}$, which corresponds to the total minimum drag of $C_{\text{D,min}} = 0.059$ as the area of the main wing was chosen as S_{W}. Table 3 presents the data used in the KiteSim simulation.

4.4 Comparison results: sway response

The Glider with the initial-size tail was seen to be highly unstable laterally in both the wind tunnel test and in the simulation. It is highlighted, however, that there are discrepancies between the physical model of the Glider and the model invoked in KiteSim and TORNADO. Basically, the discrepancies arose by virtue of tolerances in the fabrication of the model.

In order to achieve lateral stability, values for the forces and moments on the vertical tail could be arbitrarily increased in KiteSim until stable flight was reached. Then, by adjusting the geometrical size of the tail in TORNADO, the values for the forces and moments on the vertical tail determined in KiteSim thereby facilitating sizing. Theoretically, the investigated configuration should exhibit stable qualities in yaw. To verify this posit, the wind tunnel model was given this sized vertical tail and tested. The model was first positioned in a static and trimmed state; and at a given instant, a disturbing force was applied to the wing in a spanwise direction. From the analysis produced by DoTrack, the response to this force in the lateral coordinate, $X(t)$ of the glider was determined. Similarly, KiteSim computes the same response, and these two sets of data as shown in Fig. 16 were compared. Both data sets show a damped behaviour that

Table 3 Data required for the KiteSim simulation

Angle of attack dependency	Side-slip dependency (per rad)	Pitch rate dependency (s/rad)	Roll rate dependency (s/rad)	Yaw rate dependency (s/rad)
(A) Aerodynamic and static derivatives computed with TORNADO				
$C_{\text{Lo}} = 0.00$	$C_{\text{Y}\beta} = -0.218$	$C_{\text{Lq}} = 0.556$	$C_{\text{Yp}} = -0.0120$	$C_{\text{Yr}} = -0.0440$
$C_{\text{L}\alpha} = 7.35$ per rad	$C_{\text{L}\beta} = -0.006\,40$	$C_{\text{Mq}} = -0.257$	$C_{\text{Lp}} = -0.248$	$C_{\text{Lr}} = 0.001\,90$
$C_{\text{Mo}} = 0.00$	$C_{\text{N}\beta} = -0.0610$		$C_{\text{Np}} = 0.000\,800$	$C_{\text{Nr}} = -0.0120$
$C_{\text{M}\alpha} = -0.920$ per rad				
(B) Minimum drag estimation				
$C_{\text{D,min}}$	$C_{\text{L,minD}}$	e_{o}		
0.0590	0.00	1.24		
(C) Moments of inertia computed from solid edge CAD				
I_{xx} (kg m^2)	I_{yy} (kg m^2)	I_{zz} (kg m^2)	I_{xz} (kg m^2)	
358	51.4	363	3.00	

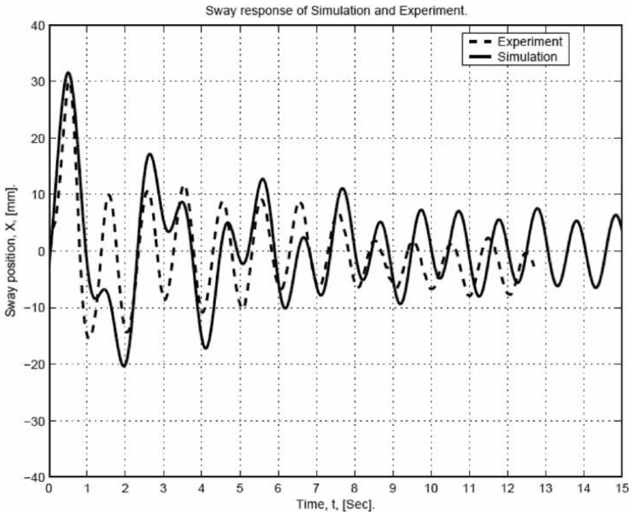

Fig. 16 Comparison between simulated and experimental sway response, the sway position $X(t)$ versus time. Both cases show a damped behaviour built up of two frequencies

is built up of two frequencies. One oscillation in side-slip angle produced a frequency of 1 Hz, whereas the one pendulum mode about the tether anchor point produced 0.8 Hz. With this evidence in place, the wind tunnel test proved to confirm the theoretical prediction of KiteSim.

5 CONCLUSION FOR BOTH PROJECTS AND LESSONS LEARNED

The collaborative teaching approach to aircraft design education was found to produce three groups of beneficiaries. The first was industry, due to the fact that the students who have experienced some of the challenges of managing the design of a high-value manufacturing product can be offered this approach. The second, through quality of education in a direct fashion, is the focal institutions, namely, EPdM and KTH. On a more subtle level, the third, indirect through quality of education, is the institutions resulting from ever-increasing numbers of international students that participate in such design projects. Undergraduates from Bristol, UK; Milan Italy; and Toulouse, France have found an opportunity to participate in conjunction with the native Canadian and Swedish undergraduates. Collectively, the collaborative teaching approach has also served as a catalyst for opening up new research opportunities as well as assisting with the introduction of new initiatives like industry internship programmes.

A synopsis of the lessons learned from experiencing the collaborative teaching approach to aircraft design education is as follows:

(a) allows opportunity to gain a greater insight into a specific technical discipline and comprehend the complex interactions;
(b) foster skills on how to interact in a goal-oriented technical team;
(c) experience some of the challenges of managing the design of a high-value product;
(d) effective communication ensures project governance;
(e) appointing a project management coordinator is key to success; achieved via structured and frequent technical group meetings;
(f) requirement for a final review to senior academic staff and industry professionals fosters a high calibre of presentation skills.

Among the conclusions of experience from flight control learning, are the following benefits:

(a) a deeper insight into the various factors affecting aircraft stability and control;
(b) appreciation of the simulation–experiment synergy;
(c) possibility to involve multi-disciplinary content matter and skills, ranging from programming in SIMULINK to building models in balsa wood to techniques in computer-based visualization.

It is worth mentioning the advantages of using MATLAB™ and SIMULINK as the development tools for both TORNADO and KiteSim. Because MATLAB™ and SIMULINK are nowadays widely used both in university and industry, undergraduates come suitably prepared when undertaking the aforementioned courses, and they have an ability to continue working with the same tools when they go to industry. Furthermore, when students ‘fly’ their own designs (even if this is just in KiteSim), the design process becomes much more interesting and captivating.

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APPENDIX

Notation

C — coefficient for non-dimensional aerodynamic parameters; coefficient for static stability derivatives

e	Oswald efficiency parameter
$\bar{F}_t$	magnitude of force within tether line (N)
k_1	coefficient of proportionality in quantifying tether line force (kg/s^2)
k_2	coefficient of proportionality in quantifying tether line force (kg/s)
M	Mach number
p	vehicle rate of roll (deg/s or rad/s)
q	vehicle rate of pitch (deg/s or rad/s)
r	vehicle rate of yaw (deg/s or rad/s)
S	reference planform area (m^2)
t	time
V	velocity (m/s)
X	sway position
α	angle of attack (deg or rad)
β	vehicle side-slip angle (deg or rad)
Γ	wing dihedral (deg)
ε	tether line elongation (m)
$\dot{\varepsilon}$	tether line deformation rate (m/s)

Subscripts

cr	critical point for drag creep, two-dimensional
CR	critical point for drag creep, three-dimensional
d	drag, two-dimensional
D	drag, three-dimensional
dd	critical point for drag divergence, two-dimensional
DD	critical point for drag divergence, three-dimensional
Do	denotes zero-lift drag
HT	horizontal tail
I	moments of inertia (kg m^2)
l	lift, two-dimensional
L	lift, three-dimensional
Lp	denotes the vehicle dumping-in-roll or resistance of vehicle to rolling motion (s/deg or s/rad)
Lq	denotes the vehicle rolling moment due to pitching motion (s/deg or s/rad)
Lr	denotes the vehicle rolling moment due to yawing motion (s/deg or s/rad)
LRC	Long-range Cruise
Lα	denotes the vehicle lift-curve slope (per degree or per radian)
Lβ	denotes the vehicle rolling moment due to side-slip or dihedral effect (per deg or per rad)
min	minimum condition
minD	minimum total drag force condition
M	moment
MCRZ	maximum cruise
Mq	denotes the vehicle pitching moment due to pitching motion (s/deg or s/rad)
Mα	denotes the vehicle moment due to angle of attack, static longitudinal stability parameter (per deg or per rad)
Np	denotes the vehicle yawing moment due to rolling motion (s/deg or s/rad)
Nr	denotes the vehicle dumping-in-yaw or resistance of vehicle to yawing motion (s/deg or s/rad)
Nβ	denotes the vehicle moment due to side-slip, static yawing stability parameter (per deg or per rad)
o	initial condition
STD	Standard or normal cruise
VT	vertical tail
W	wing
xx	denotes about the longitudinal or x-axis
xz	denotes a product of inertia between x and z axes
yy	denotes about the lateral or y-axis
Yp	denotes the vehicle side force due to rolling motion (s/deg or s/rad)
Yr	denotes the vehicle side force due to yawing motion (s/deg or s/rad)
$Y\beta$	denotes the vehicle side force due to side-slip (per deg or per rad)
zz	denotes about the vertical or z-axis