Aircraft Engineering and Aerospace Technology

Aerodynamic wing shape optimization based on the computational design framework CEASIOM

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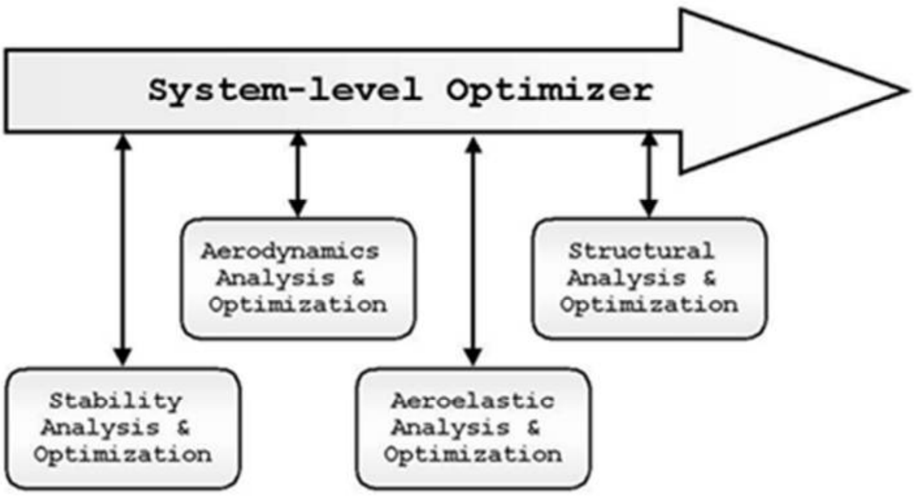
Introduction

To achieve a concept that satisfies the design requirement, usually a mathematical optimization process is followed. With the design initial layout as the baseline, we can formulate an optimization problem using data computed by the multi-disciplinary analysis, to get the best performance w.r.t. the design requirements. This process is a typical MDO process for conceptual design. The recent advances in computer performance and simulation capabilities provide access to sophisticated codes and efficient analysis modules, in all aeronautical disciplines.

MDO can be described as a collection of mathematical techniques for multivariable optimization in which the optimization clearly crosses disciplinary boundaries. This optimization problem can be posed to be very complicated. Therefore, it must be approached by decomposition. Traditional decomposition leads to sub-problems of aerodynamic shape optimization coupled to structural design only by simplified constraints such as on wing thickness, limits on wing root bending moment, etc. Even wing shape optimization is complex enough, and is in practice carried out with a combination of mathematical tools and engineer know-how. Figure 1 shows the MDO group maybe be broken down into a number of weakly-interconnected sub-groups, allowing the engineer to perform separate optimizations within these sub-groups, coordinated and linked such that the entire system is optimized when the separate optimizations are brought together.

Figure 1 MDO process by decomposition.



The physics based analysis in MDAO (Multidisciplinary Analysis and Optimization) applications requires not only disciplinary expertise, but also the management of cross-disciplinary model consistency. The need for a unified model supporting multiple analysis modules has been widely recognized in the aircraft design community. Many successful integrated design systems have been developed, to automate the design process from top level aircraft requirement (TLAR) to a design solution (Torenbeek (1982) and Raymer (2006)). Nevertheless, the state of the art in aircraft pre-design environment is often still based on automated, but monolithic design codes which cannot easily be adapted to cope with new configurations, or replaced when improved disciplinary analysis modules become available (Kroo et.al., 2005). The challenge is even greater if analysis modules developed by different parties are to be integrated in the same design process. On the other hand distributed design approaches offer the desired flexibility, but need to guarantee consistency among the disciplinary abstractions generated within the design process.

This paper focuses on the aerodynamic shape optimization (ASO) technology for wing design, which is a sub-task for MDO. The optimization is carried out based on the computational design framework CEASIOM[a]. It requires analysis in different modules within the design process including geometry modeling, parameterization, meshing and simulation. The interaction between several disciplines is achieved by the common language CPACS[b] (Common Parametric Aircraft Configuration Schema), adopted by CEASIOM in its latest version, dubbed CPACScreator (Ciampa et.al., 2013). CEASIOM Aerodynamic Shape Optimization, or CEASIOM-ASO approach is reviewed here and two test cases are shown to prove that this approach is promising, especially for highly-nonlinear complex aerodynamic optimization problems.

Collaborative Design Environment for Wing Shape Design

The collaborative design environment used for wing shape design is CPACS-adopted CEASIOM. This section CPACS and CEASIOM framework are briefly described.

Common Parametric Aircraft Configuration Schema

MDO conceptual design is carried out by teams with different fields of expertise, requiring different analysis modules. To communicate with each other for integrated design, $n(n-1)$ bi-lateral interfaces are needed. In a *data-centric* framework, each analysis module communicates with all other via a common namespace, thus the cost for data collaboration is reduced to $2n$, and this common namespace is preferable to be adopted into a data-centric framework. The German Aerospace Center (DLR) has been developing a de-centralized collaborative design

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[a] www.ceasiom.com
[b] http://code.google.com/p/cpacs

environment within the 7th EU CRESCENDO Project, to foster collaboration among disciplinary specialists, and integrate disciplinary expertise into a collaborative overall aircraft design process (Zill, 2011 and Zill, 2012). The design environment is built on the central data model CPACS an arbitrary number of analysis modules, and on the open source design framework RCE[c] (Remote Component Environment), enabling the orchestration of the design workflows. CPACS is a data format based on XML technologies, and used for the interdisciplinary exchange of product and process data between heterogeneous analysis codes and name space.

MDO framework in conceptual design

CEASIOM, the Computer-based Environment for Aircraft Synthesis and Integrated Optimisation Methods, developed within the European 6th Framework Programme SimSAC (Simulating Aircraft Stability And Control Characteristics for Use in Conceptual Design) (Rizzi, 2011), is a framework for conceptual aircraft design that integrates discipline-specific tools like: CAD & mesh generation, CFD, stability & control analysis, etc., all for the purpose of early preliminary design. The CEASIOM framework offers possible ways to increase the concurrency and agility of the classical conceptual-preliminary process by its four core functions: geometry & meshing (Tomac and Eller, 2011), CFD (Da Ronch et. al., 2011), aeroelasticity (Cavagna et. al., 2011), and flight dynamics (Goetzendorf-Grabowski et. al., 2011), the desired attributes for MDO in conceptual design.

The New CEASIOM, or CPACScreator, connects CEASIOIM to CPACS universe. The effort was made to create a flexible, extensible, and comprehensive data centric framework for analysis, simulation, design and optimization tasks. The new features are:

- Adopting the CPACS XML data formats; and
- Graphical tools for editing the aircraft design data.

The CEASIOM-ASO approach is developed on top of New CEASIOM (Zhang, 2015). Most notably benefits are: (i) higher fidelity geometry and meshable model from CPACS; (ii) higher-fidelity CFD via *sumo-Edge* module in CEASIOM.

Parameterization and Geometry Modeling for Wings

There are many ways to parameterize a wing, to produce either the lofted wing surface, or the set of surface mesh points. For example, the wing surface can be lofted through airfoil stacks, or the geometry can be represented by

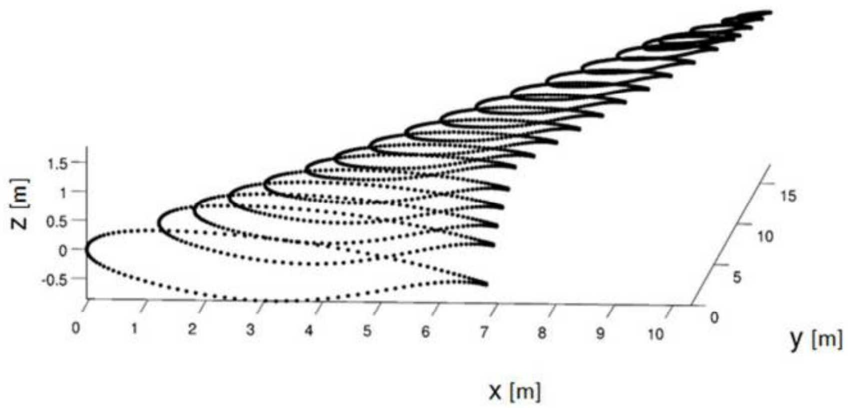
[c] http://code.google.com/a/eclipselabs.org/p/rce/

modelling the perturbations of a “baseline” shape (Amoignon, 2014). The latter technique can also perturb off-surface mesh points, by so-called “mesh-deformation” (Jakobsson and Amoignon, 2005). CEASIOM-ASO uses the former one, followed the default wing shape definition in CPACS language. Although the CAD-free parameterization techniques such as mesh deformation have been more frequently proposed (Mohammadi et.al. 2000 and Kenway et.al. 2010), the re-meshing is easy and robust if a smooth geometry is given and a reliable and fast meshing tool is provided. In CEASIOM-ASO the mesh is thus updated by re-meshing using *sumo*, a tool for rapid automatic Euler and RANS meshing (Tomac and Eller, 2011). This section shows the geometry modelling and parameterization techniques used for CEASIOM-ASO, including the modelling of trailing edge movable surfaces using morphing technique.

Wings as airfoil stacks

Airfoil sections are the most important building block of aerodynamic geometry. In most software systems for aircraft shape definition, the defining stations are chordwise cuts. This is the same for CEASIOM-ASO. The wing surface parameterization is decomposed into parameterization of n station of airfoils. The first defining station starts at the symmetry plane (wing root), and the last defining station locates at the wing’s theoretical tip. Each airfoil (defined as scaled to leading edge at the origin to trailing edge at [1, 0]) is rotated by an incidence, translated to the defining station leading edge, then scaled to match the projected planform chord. The wing surface is lofted from the sections by Bézier or Bspline surfaces (Gallier, 2013) in *sumo*.

Figure 2 Wing surface creation using N sets of airfoil point clouds positioned in 3D.



Airfoil shape definition

<u>Bézier curves</u>

Bézier parametric polynomials to define the airfoil shape is a simple and robust technique (Farin et.al 2002, Gallier 2013, de Boor 1978). It can conserve geometrical properties like leading edge radius and trailing edge angle, and foil definitions by a set of coordinates can be approximated simply, often as a least-square fitting problem. Melin and Amadori (2011) developed a technique that uses four pieces of cubic Bezier curves to parameterize an airfoil within a reasonable error level, as seen in Figure 3.

CEASIOM-ASO uses a modified technique by decomposing the airfoil shape by thickness distributions and cambers with cubic Bezier curves (see Figure 4), and the number of design variables is reduced to from 14 to 10 (5 for thickness, 4 for camber line, 1 for twist). Details can be referred from Zhang et. al., 2012. A parametric Bézier curve is represented by the equation below,

$$P(t) = \sum_{i=0}^{n} B_i^n(t) \cdot CP_i \tag{1}$$

where $B_i^n(x)$ is the Bernstein polynomial $B_i^n(x) = \binom{n}{i}(1-t)^{n-i}t^i$, CP are the control points. For cubic Bézier curves $n = 3$.

Figure 3 Airfoil parameterization by 4 pieces of cubic Bézier curves, developed by Melin and Amadori (2011)

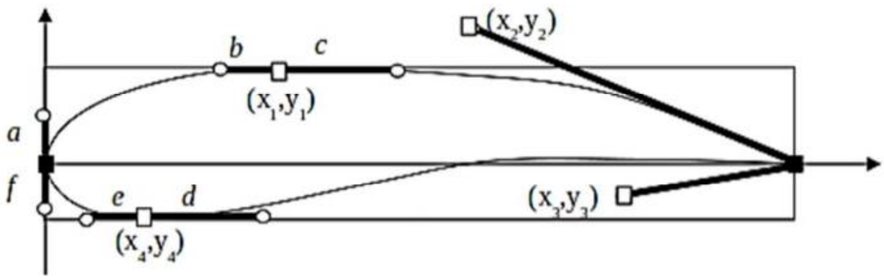
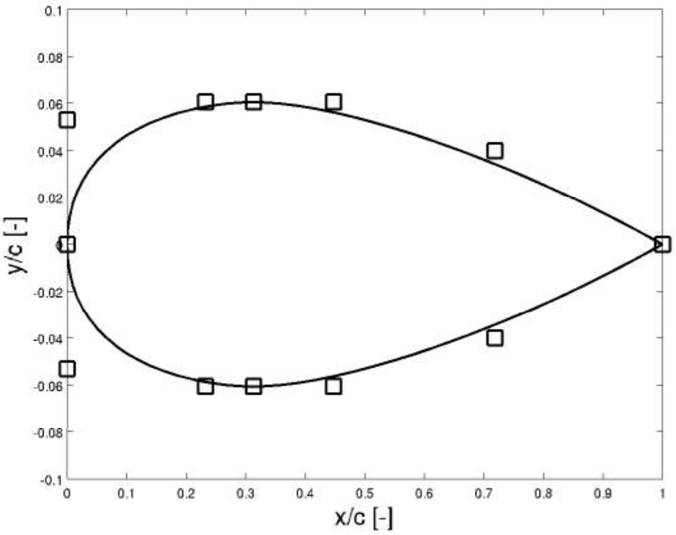
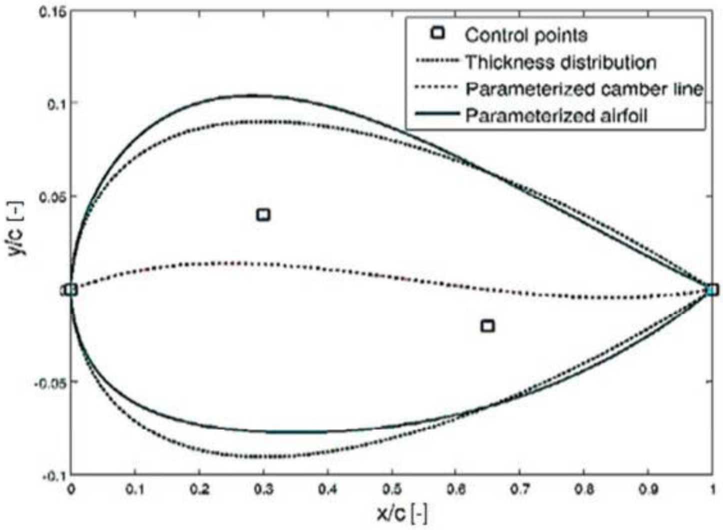


Figure 4 Airfoil parameterized by thickness and camber

(a) Thickness distribution parameterized by cubic Bézier curves used in CEASIOM-ASO



(b) Camber line represented by one cubic Bézier curve used in CEASIOM-ASO



Class function & Shape function

The Class-Shape-Transformation (CST) method was pioneered by Kulfan (2008) and Ricci (2014). The airfoil is represented by a series of Bernstein polynomials multiplied by a so-called class function that is determined by the airfoil shape type. It can also be modified to represent the airfoil by thickness distribution and cambers and implemented in CEASIOM-ASO. The thickness distribution (T) y_T is to define the shape function S_T with zero camber, while the camber shape(c) y_c is to define the shape function S_c with zero thickness.

$$S_T(x) = \sum_{i=0}^{n} A_{Ti} S_i(x) \tag{2}$$

$$y_T = C(x) S_T(x) \tag{3}$$

$$S_c(x) = \sum_{i=0}^{n} A_{ci} S_i(x) \tag{4}$$

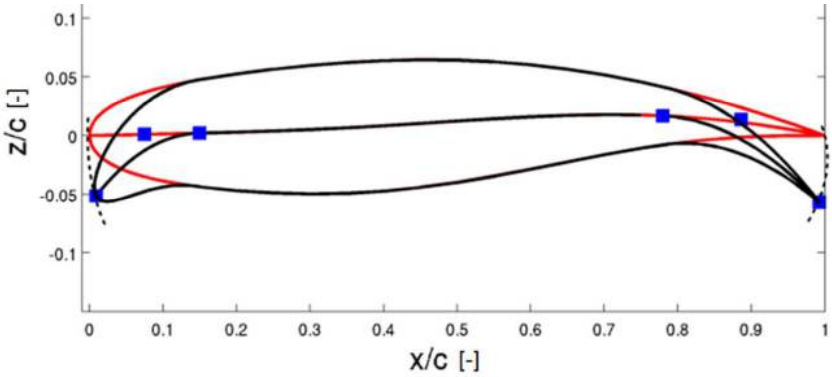
$$y_c = S_c(x) \tag{5}$$

where $S_i(x)$ is the Bernstein polynomials of the previous section,, A_{Ti} and A_{ci} are the coefficients added to the shape function that define the thickness and camber shape respectively, $C(x)$ is the class function depending on the airfoil shape, for example $C(x) = \sqrt{x}(1-x)$ for a shape with round nose and point aft-body. Note that the first term of A_{Ti} (or A_{T0}) defines the LE radius ($A_{T0} = \sqrt{2R_{LE}}$) (Kulfan, 2008), that we always want to fix or predefine. Similarly, the first term of A_{ci} (or A_{T0}) is always 0 (zero LE radius) since the camber line has zero thickness. Both the number of A_T and A_c coefficients are reduced to (n) if we want to fix the LE radius of the airfoil. A fourth-order Bernstein polynomial $n = 4$ is chosen, thus the number of design variables for an untwisted airfoil is 4+4=8, plus 1 for local twist. By using a modified fourth-order CST, 9 design variables are used to represent one airfoil section.

Leading edge / trailing edge morphing surfaces

The control surfaces/flap can be modeled using morphing strategy. As an extension to CPACS, the morphing strategy is incorporated into the existing parameterization approach. It is implemented by merging various airfoil parameterization methods with the original camber line deformed by quadratic Bézier curves and the thickness distribution is preserved. The leading and/or trailing edge is deflected by a deflection angle provided that the hinge line is known, see Figure 4. Two more design variables LE deflection angle and TE deflection angle are added to each section if the morphing surfaces are considered.

Figure 4 The geometric parameters describing the morphing airfoil for optimization.



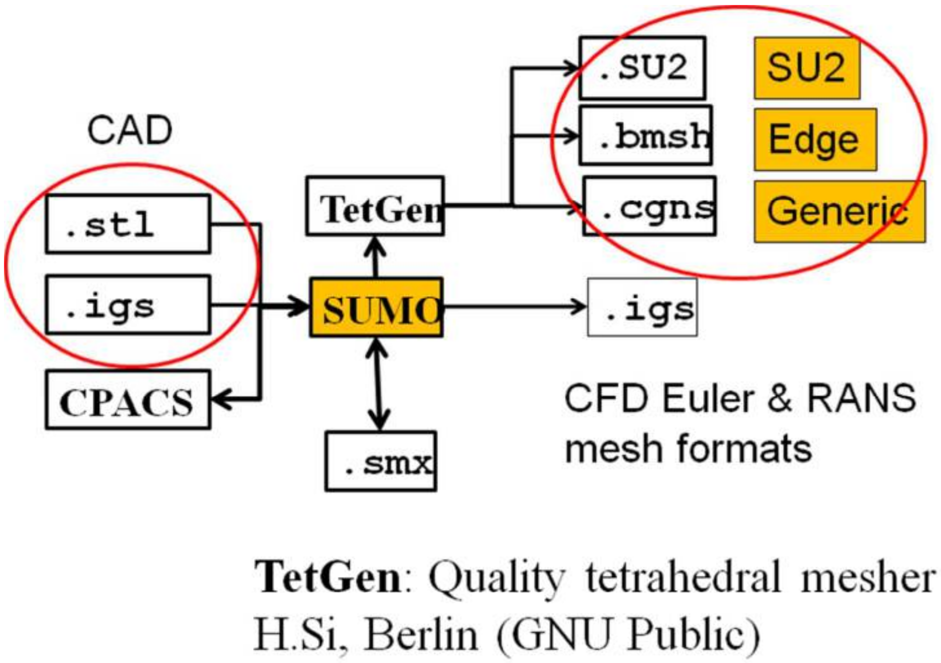
Rapid Meshing

The SUrface MOdeler[d], *sumo*, developed by Dr. David Eller, KTH, is a graphical tool aimed at rapid creation of aircraft geometries and automatic surface mesh generation. It stores the cross-sectional information (points) as skeletons for the components e.g., wings, fuselages, nacelles, and pylons. All the surfaces are represented by bi-parametric patches of the form $(x, y, z) = S(u, v)$, where at least the first derivatives with respect to the parameters *u* and *v* are continuous *sumo* across patch boundaries and the parameterization is such that G1-continuity ensues. It provides an easy-to-change environment to modify/re-construct the geometry by specifying the global or/and local leading edge positions, cross-section points, twists, rotations, etc., which are the parameters we control. *sumo* lofts the geometry and generates high-quality surface triangular grids by automatically trimming and closing the surfaces. For version 2.5.4 and above it has an “overlay” function that makes the geometry as close as possible to a imported CAD geometry, e.g., in STL or IGES format. Together with the *TetGen* (Si, 2013) automatic tetrahedral mesh generator *sumo* can provide a high-quality volume mesh for Euler computation. Through the recently developed Pentagrow function (Tomac, 2014) it will automatically create a prismatic boundary layer mesh for RANS computations. To improve mesh quality, users can control the mesh criteria and it can be saved for next time. The volume mesh format supported are standard CGNS, and the native *.bmsh* format for the Swedish national aerodynamics flow solver Edge.

The aircraft surfaces can be lofted with CPACS parameters, parameterized in *sumo* by patches of Bézier surfaces. CPACSCreator works as a gateway to connect CPACS model XML to physical-based grids for CFD analysis (Ciampa et.al., 2013). It is a preprocessor of *sumo*, when the non-meshable geometric models from other design sources are brought via CPACS. Figure 9 shows that the other sources of CAD information stored in CPACS are imported into *sumo* for grids generation, and exported as different mesh formats for different CFD solvers in CEASIOM. Other analysis can then be done after CFD using CEASIOM analysis suite such as Stability & Control analysis.

Figure 5 From CAD lofting to computational grids via *sumo*.

[d] http://www.larosterna.com/sumo.html



CEASIOM Aerodynamic Shape Optimization (CEASIOM-ASO)

CEASIOM as a data-centric, computational design framework, it has many design modules/disciplines coupled with each other, which has a potential for MDO. However, it lacks of an optimization tool, even for a single discipline. CEASIOM-ASO utilizes CEASIOM existing modules with a series systematic algorithms from geometry modelling and parameterization to design technique, implemented in *MATLAB*, adding its aerodynamic shape optimization functionality. The goal of CEASIOM-ASO is to carry out ASO without adding numerical algorithms, but adding engineering *procedures*, so that the current CEASIOM user can do aerodynamic shape optimization on her own by learning/implementing those procedures.

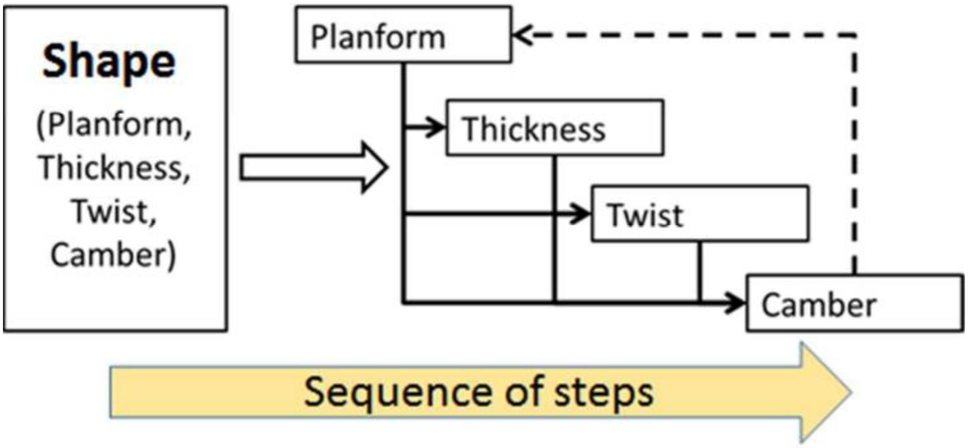
CEASIOM-ASO uses the *MATLAB Optimization Toolbox* for optimization using gradient-based algorithms. The optimization requires the user to define the cost function (usually the drag) along with the constraints, and then seeks the solution to the constrained optimization problem by mathematical algorithms for non-linear optimizations.

In CEASIOM-ASO the number of design parameters is in order of o(10), which allows the gradient that indicates how to change the geometry in order to reduce the cost function to be computed by finite differences without costing much more time compared with solving adjoint equations to flow equations. The user provided gradient can be computed by finite differences with “embarrassingly parallel” with reasonable computation time. CEASIOM-ASO uses “embarrassingly parallelization” for speed-up, and will be explained later.

Design procedure

The wing design is a complex optimization problem and it is more convenient to solve it by some procedures rather than a complicated (sometimes may get failed) numerical algorithm. It is customary to group the design parameters and use each group in turn in a coordinated iterative process. The design parameters can be categorized into several weakly-coupled groups, such as wing planform, twist, thickness distribution, and the airfoil camber line, and the design is carried out within an iterative process, as shown in Figure 6.

Figure 6 CEASIOM-ASO sequential design procedure.



The practical approach requires information in two sets: one for 2D airfoil (= wing cross section) definition and the other for the 3D planform (twist, dihedral, etc.). It is customary to first work with a fixed planform, starting with a planar wing and adding the camber and twist on it. The design can be broken down in a *sequential approach*:

1. Start with the planar wing, determine the *thickness distribution* of each section, that relates to wave drag, the shocks, and the wing box capacity;
2. Then choose the cambers and twists (varied as combination) design, that produce correct lift with desired span loads (small lift-induced drag), wing root bending moment and acceptable pitching moment;
3. Keeping the thickness, twist and camber, vary the planform;
4. If design criteria are not met, go back to 1.

If the wing planform is fixed, step 3 will be removed. The generated wing shape, as represented as a number of sections in CPACS, can be evaluated by linear aerodynamics such as vortex lattice methods as done by Nangia et.al. (2006), or Euler CFD for transonic as done for a Blended Wing-Body, Zhang et.al. (2012). The design needs to be subject to some constraints regarding to the design goal and stability issues. It will be shown in the following section as application examples of CEASIOM-ASO design approach.

Problem formulation

In each stage of sequential design, the design is to solve a non-linear constraint optimization problem,

$$\begin{cases} \min : J(w,X), \quad s.t.: \\ \quad C_L(w,X) \geq C_L^0 \\ \quad C_m(w,X) = C_m^0 \\ g_j(X_\Gamma) \leq 0, \;\; 1 \leq j \leq m \end{cases} \tag{6}$$

Where X is the mesh coordinates vector, X_Γ is the surface of the geometry, w is the vector of all flow unknowns (density, velocity and pressure) at all nodes in the mesh X, and g_j are the geometric constraints. The cost function J is selected by the designer, which might be the drag coefficient $J = C_D$, the drag to lift ratio $J = \frac{C_D}{C_L}$, or the pressure difference $J = \int (C_p - C_{p,d})^2 d\Omega$ if an inverse design problem is being posed. Particularly, we have the mesh generation algorithms

$$M(X, X_\Gamma) = 0 \tag{7}$$

and the surface parameterization algorithm

$$S(X_\Gamma, p) = 0 \tag{8}.$$

Where p is the vector of design parameters being optimized.

The discretized flow equation at the design condition (M, α) can be written as:

$$R(w_k, X \mid M, \alpha) = 0 \tag{9}$$

A change in p will give a new surface S which will correspond to a new mesh X, thus new flow solutions are obtained.

Design constraints

A satisfactory wing design must demonstrate good performance throughout the flight envelope. The design is therefore subject to a set of constraints, different for different flight conditions. Those constraints selected by designers, as specified in Eqn (6), are the “engineer’s knobs” to influence the design. The design of most transport wings follows the time-honored guidelines for simple isobar pattern at design speed. Further off-design characteristics have to be acceptable. This implies suitable thickness distribution (fuel volume) and local C_L and pitch stability constraints. Camber and twist therefore need to be designed within reasonable planform geometry parameters, without forgetting the aero-elastic behavior as the design process advances.

Some design considerations are specified as follows:

- The thickness needs to follow the thickness taper algorithm that was applied by Homes and Hjelte (1953) at KTH. The overall thickness should reduce from the central towards the tips which may cause a significant reduction of the velocity increments because of the more three-dimensional nature of the flow.
- The local twist needs *wash-out*, that the lift distribution across the span of the wing is reduced. This design ensures that the wing roots carry more loads than the tips that avoids wing tip stall and aileron ineffectiveness.
- The pitching moment must be sufficient to maintain the stability of the aircraft. Normally, the following two conditions need to be satisfied: 1) a certain static margin (SM) has to be achieved (5%-10% for a conventional aircraft); 2) the aircraft should be trimmed at cruise point. Finding out the position of the neutral point (NP) at the beginning of the design is very helpful.
- The root bending moment should be considered in the second and later iterations as a first step towards aero-structural design. The wing bending might cause aeroelastic problems such as flutter or aileron reversal. A practical factor to look into is the local C_L on the wing.

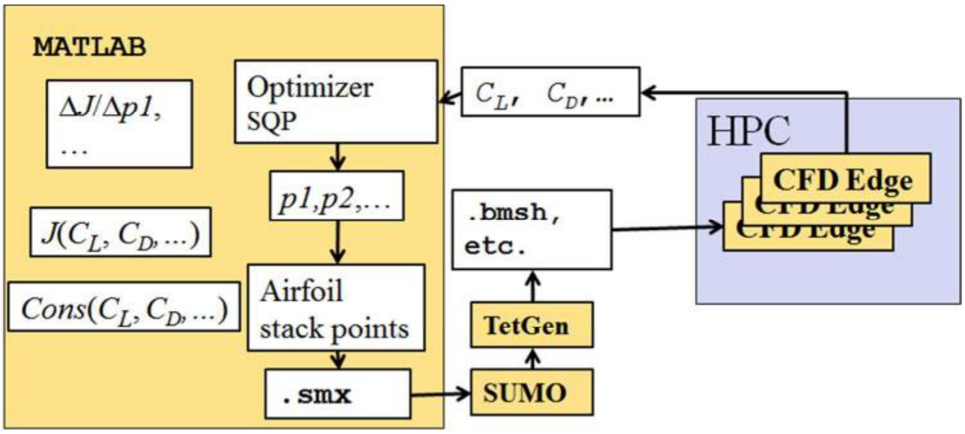
Design loop

Figure 7 shows the CEASIOM-ASO design loop. It uses the gradient-based algorithms in the *MATLAB Optimization Toolbox*, for example the Sequential Quadratic Programming (SQP). To save computation time, the user-defined gradient is calculated by finite differences by parallel computing. The speedup, proportional to the number of parameters, is significant since the gradient computations are “embarrassingly parallelization”. The tool is built by a set of Unix scripts which start jobs, move files, etc..

The user has to select the CPACS parameters to vary, and define the constraints, etc., as required by the optimization routines. The *MATLAB* program translates the (anonymous) parameter vector $\mathbf{p} = (p1, p2,....)$ seen by the optimizer into CPACS variables, writes the input file to *sumo* which generates the CFD meshes, creates the named input files for the CFD jobs, and sends the set of computations to a compute cluster. It then patiently waits for the CFD jobs to finish, compiles their results, and goes on to update the parameters.

The loose coupling between parameters and volume meshes is beneficial in the sense of allowing simple exchange of optimizers, mesh generators, and CFD solvers. However, it does *not* guarantee differentiability of the objective or constraints, which would be required for properties like quadratic termination of Quasi-Newton-like optimization algorithms. Nevertheless the optimization has worked as expected.

Figure 7 CEASIOM-ASO MATLAB Script.



Embarrassingly parallelization for gradient evaluation

The gradient-based optimization requires the gradient of the cost function J to be calculated to find the search direction for every iteration. The gradient for this highly non-linear problem stated in Eqn (6) is always calculated by finite-difference method in CEASIOM-ASO, i.e.,

$$\nabla J(p) = \frac{J(p+\Delta p) - J(p)}{\Delta p} \tag{9}$$

Where the number of design parameter p is of order o(10), typically a 40-element vector, and Δp is the small variation value. Since all the geometric parameters in p are independent for calculating the gradient ∇J, the optimization can be speeded-up by calculating the gradient using "embarrassingly parallelization": all derivatives are computed at once, each one on its own cluster node. Note that the queuing and data handling between local machine and clusters are done by *python* scripts, the re-meshing is called in *bash* shell. Details can be found in Zhang and Tomac (2012).

Figure 8 shows the total time distribution over one function iteration for 6 parameters using *embarrassingly parallelization* for gradient evaluation. One optimization iteration can be done only if all jobs (i.e., n parameters) are done, otherwise the gradient evaluation will be delayed, no matter which process has delay the whole situation (the meshing time, queuing time, CFD computation time, etc.). This is here the name "embarrassingly parallelization" is from. Although the queuing and meshing time play a more significant role in the total time than expected, the parallelization accelerate the total time a lot compared with serial computation whose consumption time is almost linearly increased with parameter number, as shown in Figure 9.

Figure 8 Total time distribution over one function iteration for 6 parameters.

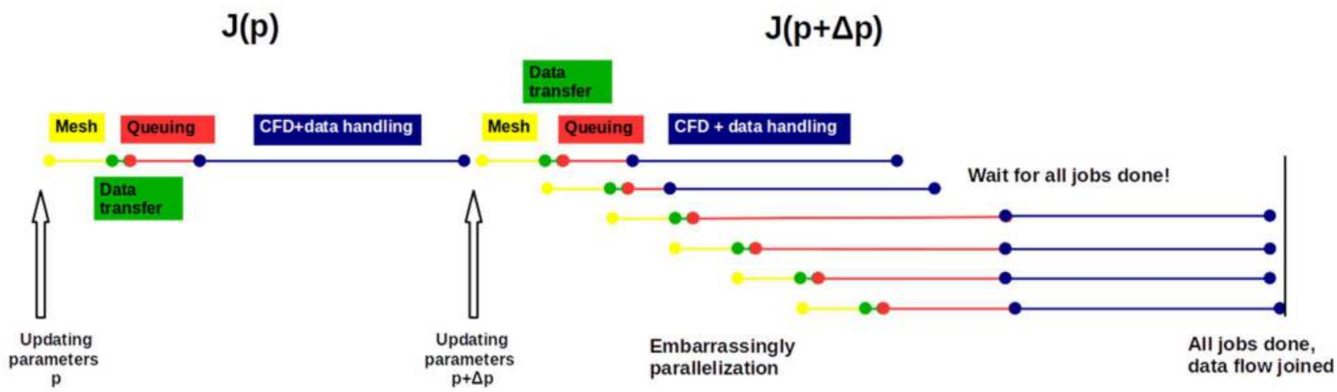
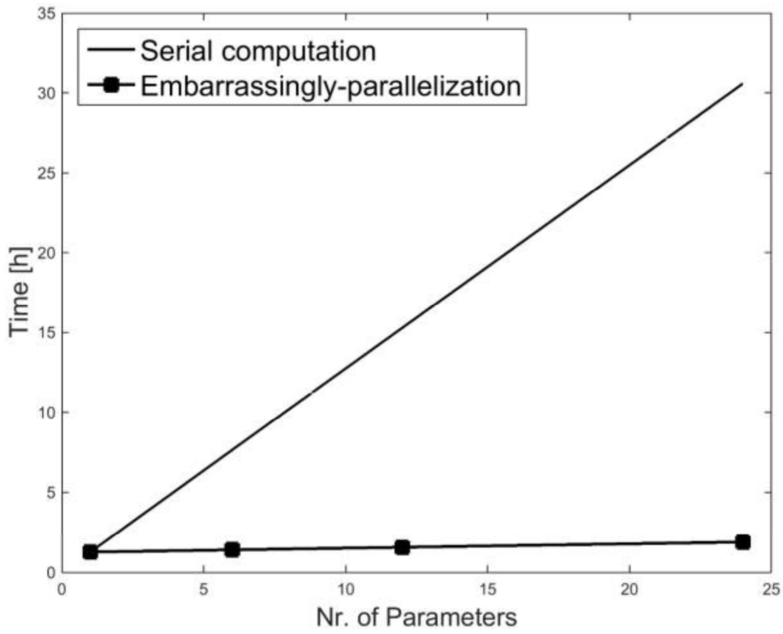


Figure 9 The total time to proceed one iteration based on gradient evaluation, provided the queuing time is always around 186 seconds (averaged), with 220-300 free nodes on the cluster. The mesh has 2 million nodes used for solving Euler equations.



The queuing time and the meshing time, usually not so long, may cause serious problems since the gradient is not calculated until all jobs are finished. As we see in Figure 8, if only one job which has long queuing time would delay the whole gradient evaluation process. To solve this, since we know the CFD computation time which is almost fixed, the dedicated nodes can be "reserved" for a certain time, each job can be run on each node for both meshing and CFD computation, until the convergence is obtained. In this case the dedicated nodes are reserved for the whole optimization process, only the prescribed jobs are running there at this moment, no queuing time is consumed.

Design Examples

Two design examples are shown in this section, to validate the CEASIOM-ASO technique. One exercise is the ONERA M6 wing and the main objective is to design a lower drag wing in transonic speed within a certain thickness. The second exercise is a more realistic design case, designing a flying wing at its cruise condition. It relies more on the iterative process that all the loosely-coupled shape parameters (planform, thickness, twist and camber) are considered in order to satisfy the design requirements.

The possibility of allowing engineer in the loop makes it less myopic than methods relying on formulation of a single optimization problem, such as the flow solver SU2 (Palacios et.al, 2014) under development. SU2 uses SciPy built-in gradient-based algorithms by solving the adjoint equation (Jameson, 1988) of the flow equations to calculate the gradient. Palacios et.al. (2015) showed an example of re-designing the NASA Common Research Model[e] (CRM) using SU2 gradient-based optimization. There are some significant difficulties. First, the optimization problem must be set up carefully by introducing the constraints "in a sequential way". Second, using mesh deformation to may result in ill-formed grids (high aspect ratio, negative volume etc.) which are unsuitable for CFD computations. Palacios et.al. (2015) employed a number of clever devices, and the best design is still minute with only 7 drag counts reduction. In this section the reader will see that how CEASIOM-ASO optimizes the wing by significantly reducing the drag.

ONERA M6 wing

The ONERA M6 wing (Schmitt and Charpin, 1979) is a thoroughly analysed small aspect ratio transonic wing, a classic CFD validation case for external flows (i.e., local supersonic flow, shocks etc.). This wing is used as a test case for CEASIOM-ASO.

Problem formulation

The problem is set-up from SU2 benchmark case. The drag should be minimized at Mach number 0.8395 and the flow is assumed to be inviscid. The maximum thickness of each section i used to define the wing should be preserved. Initial angle of attack is 3.06° where $C_L = 0.28641$. There is a case study of comparison the design results by using SU2 and CEASIOM-ASO on ONERA M6 wing, done by Zhang (2015.)

$$\begin{cases} \min : C_D, \qquad s.t.: \\ C_L \geq 0.2864 \\ Mach = 0.8395 \\ t_{i,\max} \geq t_{i,specified} \end{cases} \tag{10}$$

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[e] commonreserachmodel.larc.nasa.gov

Design results

The design of M6 wing is carried out by CEASIOM-ASO. First, the twist optimization is carried out following Eqn. (10), with three stations along the wing, the root twist is fixed at zero, no camber or thickness change. The drag is reduced by 7 counts from 144 counts with 2 degrees of freedom after 3 design cycles. Then the thickness optimization is applied to the twisted wing. After 7 design cycles, the drag is further reduced to 103 counts, with 28 degrees of freedom at 4 design stations. For this test case, as Figure 10 shows, after twist and thickness optimizations respectively, 9 design cycles were run, the drag is reduced by 28.5% with all the constraints held. The computational mesh has around 1 million nodes, computed on a HP-Z260 workstation with 8 processors, costing 6.9 min computation time for each full cycle.

Figure 10 Design cycles indicats the aerodynamic coefficients C_L and C_D computed by Edge Euler for the ONERA M6 baseline wing, and for CEASIOM-ASO designs.

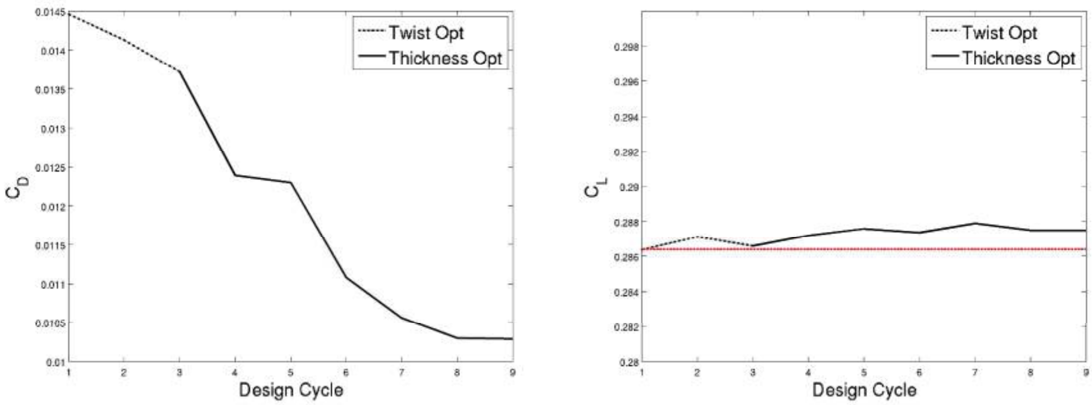
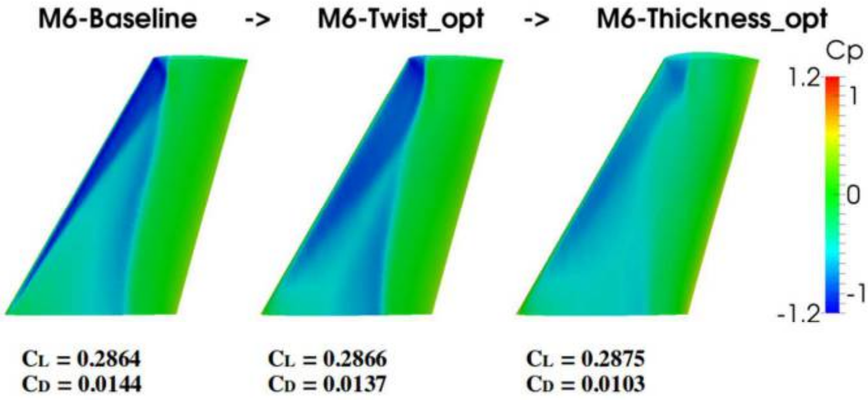


Figure 11 shows the upper surface C_p designed from the sequential design. Inspection of the pressure patterns and the shock footprints indicates only little gain in wave drag from the twist, although quite aggressive. Reduction of induced drag is harder to observe. However, the thickness optimization essentially eliminates the lambda shock, and the baseline suction spike/shock at the tip is reduced. It would see that for only considering twist and thickness change in CEASIOM-ASO, it has actually improved the wing pressure field by eliminating the shock waves.

Figure 11 Upper surface C_p for ONERA M6 baseline and optimized design on the twist and thickness, using CEASIOM-ASO.



Blended Wing Body optimization

The Blended Wing Body, or BWB, comes from EU project MOB (Multidisciplinary Optimisation of a Blended Wing Body). The baseline configuration in CPACS format was provided by German Aerospace Center (DLR) (Ciampa et.al., 2011). This flying wing is designed to cruise at transonic speed with Mach number 0.8 at altitude 10 km. A good deal of the aerodynamic design work has been carried out with the Euler-based optimization techniques and the results have demonstrated as a well-posed example of using CEASIOM-ASO for wing design.

Problem formulation

The goal is to fly at a maximum L/D around 22 for a clean wing, with designed cruise condition at Mach number 0.8 with $C_L = 0.3$. The non-linear optimization problem can be written in the following form:

$$\begin{cases} \min : C_D, \quad s.t.: \\ C_L = 0.3 \\ C_m \approx 0 \\ Mach = 0.8 \\ t_{inner} \geq 0.9 \cdot t_{inner,baseline} \end{cases} \tag{11}$$

Where $C_m \approx 0$ to ensure a "trimmed" aircraft, and the thickness constraints follow the fact that the volume of the inner sections (i.e. the body part) should be almost maintained to accommodate the passengers.

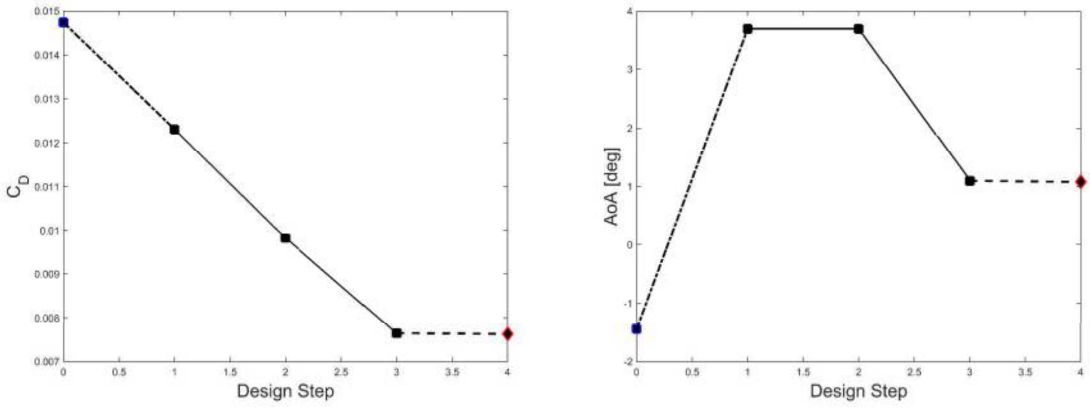
Design results

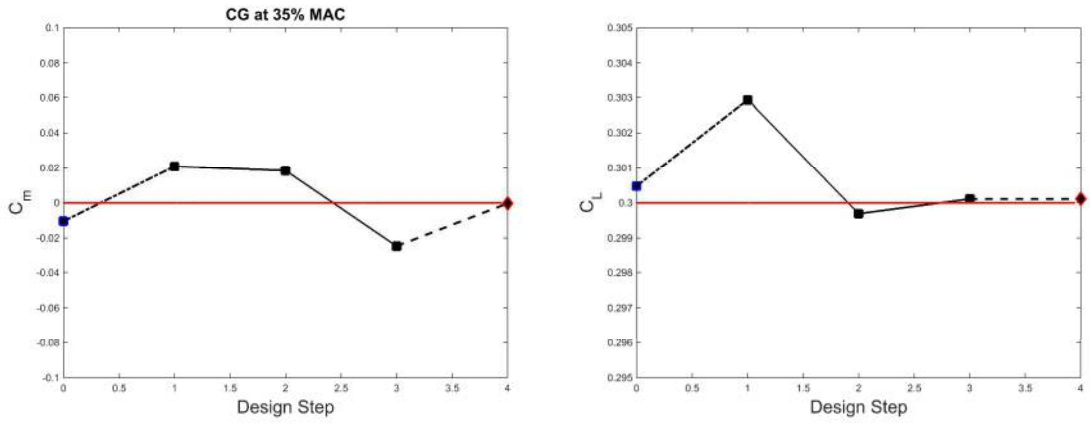
The design followed the "sequential approach" discussed above, using CEASIOM-ASO design loop showed in Figure 10 for each design step. The baseline configuration has 147.4 drag counts, and the optimal design gets around 45% reduction, down to 76.3 drag counts, with all the constraints fulfilled. The solutions are from Euler equations and the mesh has approximated 3.5 million nodes.

The baseline, or the 0th step, has too high local Mach number up to 1.9 on the upper surface, with too high tip loads ("washed-in" twist distribution). The design starts by removing all the natural cambers and twists, with only thickness distribution left. This is shown in Figure 12 as 1st design step. The process of each design step for designing the BWB is summarized as following:

0. The baseline configuration in CPACS format from DLR, which was raised up in MOB project;
1. The "no twist and camber" version of the baseline configuration, the planar wing with only thickness distributions left;
2. The optimized planar wing with determined thickness distributions which fulfils the constraints on C_L and the thickness (no constraint on C_m);
3. The wing with optimized twist and camber (combined) which fulfils the constraint on C_L (thickness constraint is already satisfied), and a loose constraint on C_m as $-0.1 < C_m < 0.1$;
4. Optimized wing with a varied planform that the outer wing shifted 3 meters, or approx.. 10% MAC forward in order to achieve the trim condition $C_m \approx 0$. Now this wing satisfies all the constraints which are set up in Eqn (10).

Figure 12 The sequential design for designing BWB, computed by EDGE Euler on a mesh with 3.5 million nodes.





Note that from 3rd step to 4th step, the only difference is to shift the outer wing to change the overall pressure distributions, so that the aerodynamic centre is moved forward while the centre of gravity is mostly unchanged. The C_L, C_D, AoA and span loading distributions are all maintained (see Figure 13 below), pitching moment coefficient is changed during this design step so that $C_m \approx 0$ with a static margin $SM \approx 4\%$ of MAC.

Figure 14 shows the solutions for the final optimized wing (4th step) compared with the initial wing, including the Mach contour plot, and geometric comparisons of thickness distributions and twists. The optimized wing is twisted to be conventionally "washed-out" instead of "washed-in". The thickness distribution follows a so-called "thickness taper" pattern (Homes and Hjelte, 1953), with an overall trend of thickness decreasing towards the wing tip. Note that the maximum thickness for the inner part is bounded. The thickness modification, again, as expected, has moved the location of maximum thickness rearward. More solutions and discussion as well as the details of the sequential design process can be found in Zhang et.al. (2012).

Figure 13 Span loading distributions (a) and local C_L (b) for the design steps from 0th (initial wing) to 3rd, from sequential design approach CEASIOM-ASO.

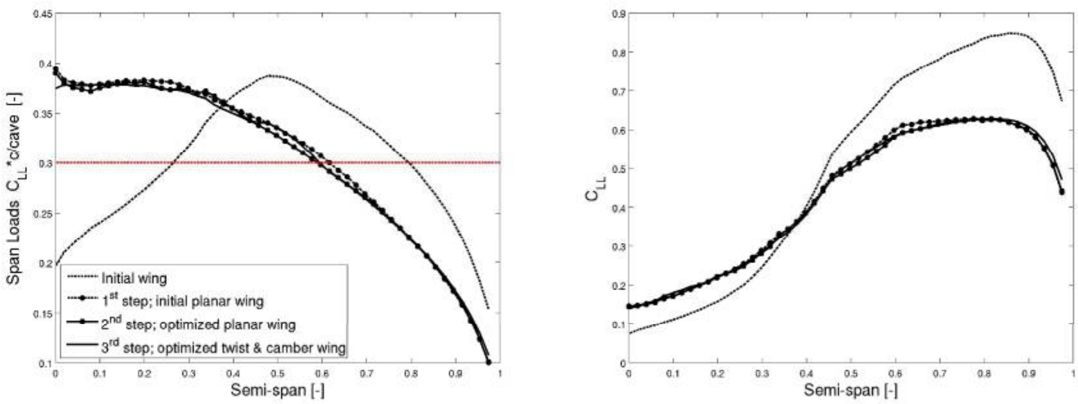
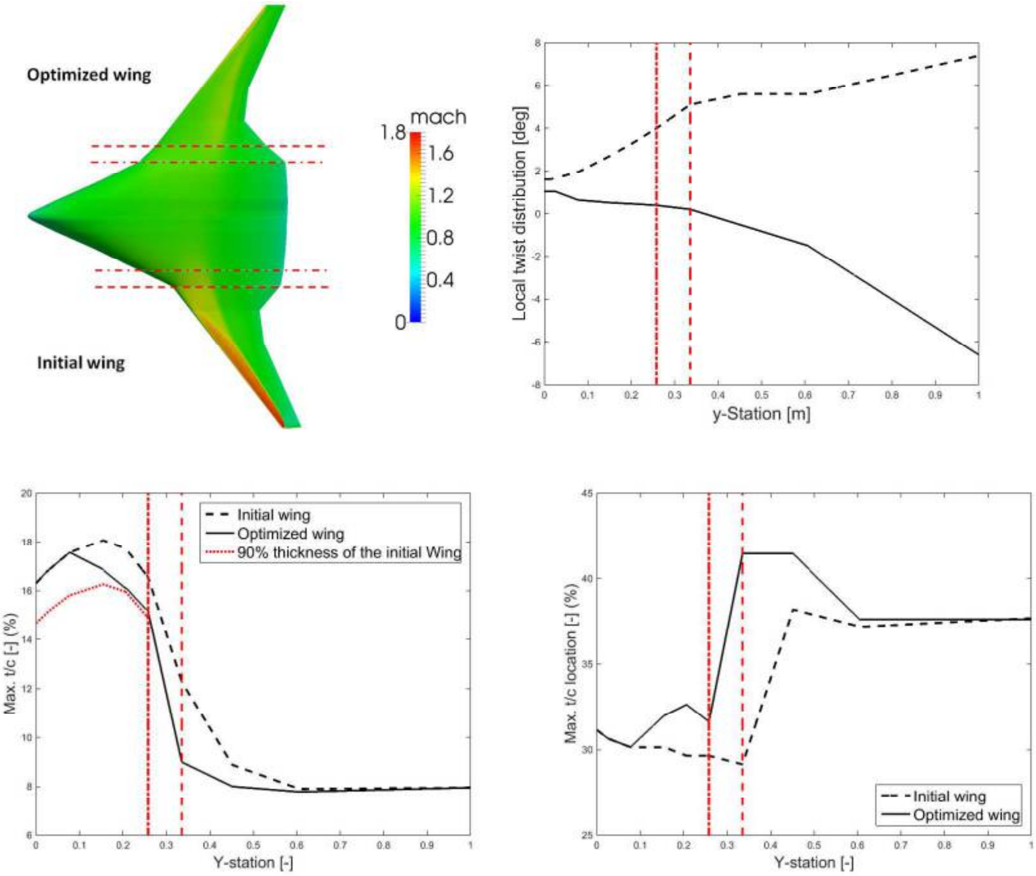


Figure 14 Solutions for optimized wing compared with initial wing, from CEASIOM-ASO, with the inner body part and (original) kink marked by dot-dashed and dashed lines respectively.



Conclusion and Discussion

This paper describes CEASIOM-ASO, the aerodynamic shape optimization implemented by *MATLAB* scripts in the conceptual design framework CEASIOM. The outstanding feature is that it is loosely coupled to the computational modules, such as geometry modeller, grid generator and flow solver. The loosely-coupling model has a number of advantages. CFD solvers and structural mechanics packages are complex and the commercial packages have data structures and application program interfaces which are proprietary with documentation not available to users. However, every package has input and output files which are necessarily well documented. The computational modules can be coupled by monitor-type programs which understand the file formats and know how to read and write the files and how to translate between different parameterizations. Several such packages such as iSight[f] and ModeFrontier[g] are commercially available for parameter optimization, uncertainty quantification etc.

The study showed that CEASIOM-ASO treats the design as a procedure, it leads a more robust and more straightforward design within an existing design framework. CEASIOM-ASO has flexible choices of objective function and constraints, breaks the optimization problem into several small sub-problems, to allow the engineer freedom to guide the design direction, offering easy and plentiful engineer interaction. It shows excellent design abilities as the design examples discussed in previous section. Moreover it is easily parallelized in order to carry on gradient-based algorithms.

Acknowledgments

Computational resources were provided by the PDC Centre for High Performance Computing (PDC-HPC) at KTH Royal Institute of Technology.

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[f] http://www.ipe.cuhk.edu.hk/Equipment_list/iSIGHT.htm
[g] http://www.esteco.com/modefrontier

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Nomenclature

Symbols

C_L	Lift coefficient [-]
C_D	Drag coefficient [-]
C_m	Pitch moment coefficient [-]
α or AoA	Angle of attack [deg]

Definitions, Acronyms and Abbreviations

OAD	
MDAO	
MDO	Overall aerodynamic optimization
ASO	Multidisciplinary Analysis and Optimization
CFD	Multidisciplinary Design and Optimization
CEASIOM	Aerodynamic Shape Optimization
	Computational Fluid Dynamics
CPACS	

Computerized environment for aircraft synthesis and integrated optimisation methods

The common parametric aircraft configuration schema