AE4-233 Advanced Design Methods 20013/2014

Part1 MDO Homework exercise:

Multi-disciplinary optimization of a wing for minimum takeoff weight

The objective of this assignment is to optimize the wing (planform and airfoil shape) of an assigned reference aircraft, in order to **minimize its maximum takeoff weight.** To this purpose a multidisciplinary optimization problem will have to be set up, based on the **IDF strategy**, including Aerodynamics, Structures and Performance as main disciplines. The level of detail will be that typical of the conceptual design phase.

To support the set-up of your MDO framework, an aerodynamic analysis tool, called *Q3DSolver*, and a structural sizing tool, called *EMWET*, will be made available via BB.

You will obtain your reference aircraft by enrolling to one of the MDO groups made available via BB. In the moment you enroll to a MDO group, a matrix of numbered aircraft data sets will become visible to you in the Assignments section on BB. **Your reference aircraft is the one with the same number as your MDO group number**. You are <u>**not**</u> allowed to choose any other aircraft.

Requirements on wing parameterization

You will parameterize the **wing planform** as a composition of at least two trapezoidal elements, in order to model **the typical kink in the wing trailing edge (TE)**. Generally, the trailing edge segment spanning from the wing root to the kink is unswept, to guarantee the maximum efficiency of the inboard high lift devices (HLD) and provide space for a landing gear support spar. Since both HLDs sizing and landing gear positioning are not part of your design system, you will have to make sure this kink is not eliminated during the optimization.

Each trapezoidal component of the wing planform will have to be parameterized in order to allow modifications of wing area, sweep, span, chord lengths, taper ratios and twist. The spanwise position of the kink will be kept at the same percentage of the total wing span as for your reference aircraft. Concerning the twist distribution of the wing, you can assume one linear twist distribution between wing root and TE kink section, and another linear distribution between the TE kink section and the wing tip.

You can assume null or constant dihedral angle(s).

Concerning the **wing outer shape**, you will have to define at least two different airfoils for the root and tip wing sections. Note that the provided aerodynamic analysis tool requires the airfoils to be defined using the 2D CST parameterization method. You shall use **CST-curves of order 5** (ATT! Curve order ≠ number of coefficients) at least, both for the upper and lower part of each airfoil.

Aerodynamic analysis (refer to MDO tutorial #3)

A MATLAB tool, called Q3DSolver is available on Blackboard to analyze the aerodynamic performance of a given wing. The implemented aerodynamics models and the functionalities of this tool, its required input and generated output files are discussed in the tutorial material and tool documentation. Note that the tool can be operated with or without viscous calculations. Wave and profile drag are computed only when the viscous calculation mode is activated. The not viscous calculation mode is faster and suitable for load estimation, but does not provide the required drag components necessary to predict the wing aerodynamic efficiency.

Initial point and design point

Concerning the **initial design point** for your wing optimization, you will use the planform of the reference aircraft assigned to your team and airfoils similar to the Withcomb airfoil presented during the MDO tutorials (for example, the Withcomb airfoil scaled to a thickness ratio of 13.5% for the wing root section and 8% for the tip section).

In order to optimize your wing design, you will use the **mid-cruise condition** as design point. The following semi-empirical relationship can be used to estimate the weight W_{des} of the aircraft (hence the design lift L_{des}) at this point:

$$L_{des}\left(\bar{x}\right) = W_{des}\left(\bar{x}\right) = \sqrt{W_{TO\_\max}\left(\bar{x}\right)\cdot\left[W_{TO\_\max}\left(\bar{x}\right) - W_{fuel}\left(\bar{x}\right)\right]}$$

Wing structural sizing & weight prediction (refer to MDO tutorial #4)

A dedicated computational tool, called EMWET is provided on BlackBoard, which is able to perform a preliminary sizing of the wing structure and estimate the overall wing weight (including the weight of fixed LE and TE edges, control surfaces, High-Lift devices, etc.). An aluminium structure is considered.

To do that, EMWET expects as input both the wing geometry (outer shape and internal layout) and the <u>sizing</u> aerodynamic loads, expressed as a spanwise distribution of lift and moment values, computed at the critical conditions given below.

Concerning the wing structural layout, you will assume a simple two spars configuration, consisting of one front spar and one back spar, delimiting the wing fuel tank. <u>**Do not**</u> consider the support spar that is often located in the inboard part of the wing, from root to kink, and used to support the main gear. It is your choice to keep the position of the spars at a fixed or variable percentage of the local chord. Typical positions of front and back spar are 15-20% and 55-60% of the local chord respectively, and accordingly to the airfoil shape and the amount of space reserved for high lift devices. The rib pitch and the type of stringers (to be selected via input file among a number of possible alternatives) can be taken constant. Note that, during the wing structural sizing process, EMWET automatically takes care of satisfying all relevant structural constraints (e.g., buckling) and delivering a minimum weight design, for the given loads and structural configuration.

Note that, in order to compute the aerodynamic loads necessary to size the wing structure with EMWET, you **cannot** use the same flight condition used to estimate the aerodynamic performance of the wing during cruise, neither the same aircraft weight! A reasonable estimation of the critical aerodynamic loads to size the wing can be obtained using the Q3DSolver at this condition: n = 2.5g, W= W_{TO_max}, h=h_{cruise},V=V_{MO} (where V_{MO} is the maximum operative speed of the aircraft, which is specified in the data set of your reference aircraft).

The necessary set of constants and reference values required for the wing structural sizing and weight estimation can be found in Table 1, or retrieved from the data set of the assigned reference aircraft.

Table 1: Constants and reference values to be used in the optimization.

Constant	Value
Aluminum elasticity modulus, E_{al}	70.10^3 N/mm^2
Aluminium tension yield stress, $\sigma_{yield,tens}$	295 N/mm^2
Aluminium compression yield stress, $\sigma_{yield,comp}$	295 N/mm^2
Aluminum density, ρ_{al}	2800 kg/m^3
Cruise speed, V_{cr}	To be taken from reference aircraft
Cruise altitude, h_{cr}	To be taken from reference aircraft
Limit load factor, n_z	+2.5
Rib Pitch	0.5 m
Maximum design wing-loading, W/S	**Not higher*** than the design wing-loading of reference aircraft (W_{TO_max}/S)
Required cruise-range	To be taken from reference aircraft
Type of stringer in wing-structure	Select one type from the manual of the structures tool EMWET
*to allow fulfilling the same takeoff and landing requirements, with same HLDs	

The total weight of the aircraft, W_{TO_max}, is determined by the following equation:

$$W_{TO\_\max}\left(\bar{x}\right) = W_{A-W} + W_{fuel}\left(\bar{x}\right) + W_{str,wing}\left(\bar{x}\right)$$

Where:

- W_{TO_max} is the maximum take-off weight of the aircraft and it is the value to be minimized in this assignment.
- W_{fuel} is the weight of the fuel required for fulfill the <u>design range</u> requirement (use the design range of your assigned reference aircraft), which must be computed by the performance discipline (see next section on Performance).
- W_{A-W} is the weight of the entire aircraft (<u>design payload</u> included), excluding the fuel and wing structure weight contributions. This value can be assumed to stay constant during the optimization process (see next section), hence it can be computed **once** using the reference aircraft data.
- $W_{str,wing}$ is the structural weight of the wing. This is the weight of the complete wing, without any fuel in the tanks, which can be determined using EMWET.

A-W group (aircraft less wing) contributions

As previously indicated, the weight contribution W_{A-W}, can be considered constant during the optimization, hence independent of the wing weight. Although this is generally not true, it is a suitable assumption at this stage of the design. This contribution can be computed once, using the data of your reference aircraft and running EMWET for the reference wing design.

Concerning the aerodynamic contribution of the A-W group (i.e., fuselage, tail and nacelles), it shall be assumed that the wing is the only component that generates lift, so the A-W group does not produce any lift. Besides that, the **drag** generated by the A-W group can be assumed constant under the flight-condition of interest and irrespective of the wing design. Please note that while the value of the A-W **drag** contribution is constant, the associated **drag-coefficient** will vary in relation with the reference area of the wing!
<u>Hint:</u> you can derive the A-W group drag contribution using the reference aircraft data provided for this assignment and assuming the following relation for the overall aircraft C_L/C_D-ratio:

$$\frac{C_L}{C_D} = \frac{C_{L,wing}}{C_{D,wing} + C_{D,A-W}}$$

Note that, in order to be able to separate $C_{D,wing}$ and $C_{D,A-W}$, you will have to run the Q3DSolver aerodynamic analysis tool **once** for the reference wing-design. For the reference aircraft you may assume an overall C_L/C_D-ratio at cruise equal to 16 (unless you get a more reliable value from literature).

Performance
The amount of fuel necessary to perform the mission (design range), can be estimated using the well-known fuel fractions method, where the Breguet-range equation is used to estimate the cruise fuel fraction (see equations below).

$$R = \frac{V}{C_T} \cdot \frac{L}{D} \cdot \ln\left(\frac{W_{start-cr}}{W_{end-cr}}\right)$$

$$W_{fuel} = \left[1 - 0.938 \cdot \frac{W_{end-cr}}{W_{start-cr}}\right] \cdot W_{TO\_\max}$$

In the equations above, $W_{start-cr}$ and W_{end-cr} are the aircraft's weights at the start and at the end of the cruise-phase, respectively.
The factor of 0.938 accounts for the fuel fractions used outside of the cruise-stage of the flight (i.e., taxi, take-off, climb, descent, etc).
For this problem, the engines' **specific fuel consumption** C_T may be taken as $1.8639\ 10^{-4}$ N/Ns (unless you get a more reliable value from literature).

Fuel tank
The amount of fuel required for a given optimized design must fit inside the wing integral fuel tanks. The fuel tanks are assumed to be placed between the front and rear spars. The following constraint applies:

$$V_{fuel}\left(\bar{x}\right) \leq V_{\tan k}\left(\bar{x}\right) \cdot f_{\tan k}$$

$$V_{fuel}\left(\bar{x}\right) = \frac{W_{fuel}\left(\bar{x}\right)}{\rho_{fuel}}$$

In which f_{tank} is a factor to account for wing-tank volume occupied by structural elements, fuel systems, unusable fuel, gas, etc. You may consider **f_{tank} as 0.93**. For aviation **fuel a density** ρ_{fuel} of $0.81715 \cdot 10^3$ kg/m^3 may be assumed.
Note, that fuel tanks generally extend till about **85% of the wing span**, being the tip area at higher risk of (lightning) strikes.

The volume of the integral fuel tanks (i.e., the part of the wing-box used to accommodate fuel) will have to be determined through some geometric evaluation and, of course, it shall be consistent with the definition of the wing shape and structural layout.

Assignment deliverables

The focus of this assignment is to solve the proposed optimization problem making use of the **Individual Discipline Feasible** (IDF) MDO scheme. The implementation will be made using Matlab and using the aerodynamic tool (Q3DSolver) and structural sizing & weight prediction tool (EMWET) provided on BB.

You shall upload on BB both the code of your Matlab implementation and a report containing the items listed below. The grading of your assignment will be based on the presence and the quality of these items.

The delivery deadline is specified on BB, in the Assignments section.

Deliverables:

Part 1: Optimization problem specification (15% of total score)

Formal specification (i.e., in mathematical terms, not only in words!) of the optimization problem, as implemented using the **Individual Discipline Feasible (IDF) strategy**.
This will include:

- The full design vector (including the surrogate variables)
- The bounds on the design variables
- The objective function (equation)
- The equality constraints (equations)
- The inequality constraints (equations)

Make sure to provide an **adequate nomenclature table**, where you shall indicate all the used symbols, their description and units.

Part 2: Description/formalization of the implemented MDO system (25% of total score)

Provide a detailed Design Structure Matrix (DSM) of your IDF scheme implementation. You can use the abstract DSM shown in the lecture notes and in the reader (ch.2; Fig 2.27) as starting point. However, in this report, you shall indicate **in detail** **all data** that are fed-forward and fed-back to, and from each component of your MDO system. In other words, don't just provide dots in your DSM, neither generic symbols such as *f, g, s*, *r*, etc.! Indicate **explicitly** all the exchanged data (e.g., A, S, b, W*,…), the definition of the residuals (e.g., r_1=W*-W,…), etc., always according to the nomenclature table of Part 1. Add arrows to indicate the data flow direction (clockwise or anticlockwise).
A good DSM is generally sufficient to clarify the structure of your implemented MDO systems, however, you can add **a few lines** to discuss some implementation details, e.g. how you map loads from the aero module to structure module, how you manage calling the aero module for design and critical conditions, etc..

ATT!! your DSM should provide evidence that all the involved disciplines are fully **uncoupled**, as prescribed by the IDF scheme. You are **not** allowed to implement any hybrid scheme to avoid, **also partially**, the full uncoupling approach of IDF.

Part 3: Technical implementation of the MDO system in Matlab and reporting of results (50% of total score)

Concerning the reporting of the optimization outcome, the following items shall be included:

- Defined computation termination criteria and tolerances and indication of which one of the defined criteria was eventually responsible for the calculation termination. Think about proper tolerances for your equality constraints!
- Detailed table comparing the characteristics of **the initial and optimum design**. You will include, for both designs, at least the following values and figures of merit:
    - objective function value
    - design vector (including surrogate variables)
    - value of constraints (including those introduced by the IDF scheme)
    - W_{fuel} fuel weight
    - W_{TO_max}
    - W_{str_wing} wing structure weight
    - V_{fuel} fuel tank volume
    - C_L, $C_{D,wing}$ and C_L/C_D
    - Plot of the spanwise lift distribution ($C \cdot C_l$) at the cruise design point
    - Plot of the spanwise drag coefficients (induced + profile + wave) at the cruise design point
    - Plot of the spanwise lift distribution at the critical conditions used (by EMWET) to size the wing
    - $C_{D,A\text{-}W}$
    - $W_{A\text{-}W}$ (this value does not change in the optimization)
    - Wing area, sweep, chords, span, aspect ratio (if not already included in the design vector)
    - Plot of the convergence history of the objective
    - Plots of the convergence history of **all** the constraints
    - Overlapped plots of the initial and final airfoils
    - Overlapped plot of the initial and final wing planform
    - plot in **isometric** view of the final wing shape

- Table including the following values:
    - Time needed to converge to optimum (or to reach termination) (use *tic..toc* in Matlab)
    - number of iterations (iteration ≠ evaluations) required
    - time required per iteration

Part 4: Critical reflection (10% of total score)
- *Briefly discuss the obtained results (for example: How the optimization modified the initial design? do these changes match your expectations? What was the effect of the constraints? What was the effect of the implemented parameterization? Etc.)*
- *Discuss any relevant implementation issues you encountered (e.g., load mapping, tools integration, convergence problems, definition of the coordination responsibility, etc.)*
- *Anything else that you would like to add*