Sequential Multi–Disciplinary Optimization for the Conceptual Design of a Blended–Wing–Body Aircraft

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Introduction

The objective of the present work is the preliminary sizing of a BWB (Blended Wing Body) passenger aircraft configuration, using a multidisciplinary modelling and optimization methodology. The aim is to ensure that all the important aspects of the design are taken into account in a concurrent way.

An existing modelling and optimization code, originally developed to optimize a high capacity version of the Prandtl–plane (see Refs. [1], [2], [3], [4], [5], and [6]; for a critical review of the methodology see Ref. [7]) has been modified and extended to the case of interest. The modifications and extension were needed to capture the features of the Blended Wing Body aircraft concept and to take properties like available volume for payload into account. The optimization code is composed of two blocks: the mathematic model of the aircraft and the optimization algorithm. The first block reproduces in a reliable way the aircraft behavior, based on a selected number of parameters/variables that allow the proper description of important aircraft features. This algorithm is used to evaluate the objective function and the constraints in order to use them in the second block – the optimizer. The objective function is a linear combination of certain figures of merit, with suitable weight factors defined by the user. The optimization method used is based on the BFGS (Broyden–Fletcher–Goldfarb–Shanno algorithm, see Ref. [8]). The constraints are treated with the penalty function method.

In using this code for the application of interest here, some problems were encountered. Specifically, a modified version of the BWB cargo configuration described in Ref. [9] was used as an initial guess for the optimization. However, this initial guess appeared not to be in the feasible region and convergence issues arose. The objective of the paper is to present a sequential optimization procedure – based on engineering judgement – that was devised to overcome this issues.

Aircraft modeling

Several models are used to derive all the figures of merit (and constraint functions) needed in the optimization. The aircraft models have been chosen as a good compromise between accuracy and computing time (see Refs. [6] and [7] for details). A common parametric geometric model is used for all the models. An important innovation here is the modelling of the trailing edge control surfaces (their deflection during cruise is a major aspect of the present study). The structural model consists of an equivalent beam model with six degrees of freedom (bending–torsional beam elements in three–dimensional space, with a shear center fixed in our case at 38% of the chord of each element). This model is used to calculate stresses and modes. The aerodynamic model is based upon a Boundary Element Method (BEM) for quasi–potential subsonic flows, with viscous correction (integral boundary layer) for the steady case, whereas the unsteady case is inviscid and treated in the frequency domain. The aeroelastic model uses a modal approach and is based upon a finite state method which allows one to reduce the flutter problem to a simple root locus problem. The aircraft equilibrium is imposed on mid–cruise condition and uses

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a Trefftz–plane approach for the evaluation of aerodynamic forces and moments. The airframe weight is evaluated from the structural model, with an empirical model used for the other components (propulsion, landing gear, etc.). Finally, the parametric model mentioned above is used to calculate the available volume for payload and fuel. Some models are described more in details in the following subsections.

The parametrized geometric model

The geometric model receives as input the design variables and gives as output the aircraft model (Fig. 1). The geometrical design variables are presented in Table 1. Not shown here are the nineteen structural design variables used to size the configuration, (*e.g.*, panel thickness).

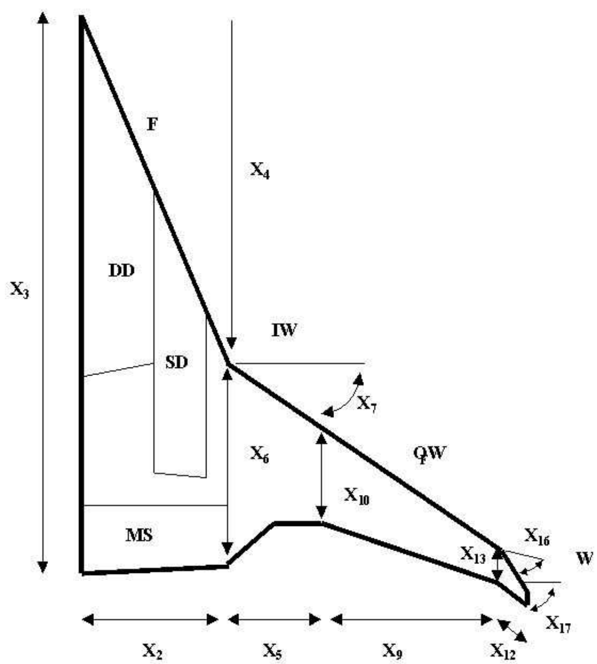


Figure 1: Sketch of the BWB model (F = Fuselage, IW = Inner Wing, OW = Outer Wing, W = Winglet, DD= Double Deck, SD = Single Deck, MS = Movable surface)

Contrary to the previous application (Prandtl–Plane wing, with fuselage prescribed), here the internal layout is considered, so as to ensure the necessary space for payload and fuel. Without going into the details, portion of the configuration has a double passenger deck and portion a single deck; a minimum height for each deck is enforced in the optimization process. The airfoils were taken from Ref. [9]. To have control over the pitch moment coefficient (CM_0) of the aircraft, the camber of the airfoils has been made adjustable through design variable X_1.

X_1	Fuselage airfoils curvature	X_{10}	Outer wing chord
X_2	Fuselage span	X_{11}	Outer wing t/c (left)
X_3	Fuselage chord (left)	X_{12}	Winglet span
X_4	Wing relative position	X_{13}	Outer wing chord (right)
X_5	Inner wing span	X_{14}	Outer wing t/c (left)
X_6	Fuselage chord (right)	X_{15}	Winglet t/c (right)
X_7	Wing sweep	X_{16}	Winglet sweep
X_8	Inner wing t/c (middle)	X_{17}	Winglet Dihedral
X_9	Outer wing span		

Table 1: The BWB design variables

Parasite Drag Estimation

The viscous drag is obtained by a viscous–flow analysis, consisting in coupling the quasi–potential three–dimensional flow with a strip–theory integral boundary layer formulation (direct iterative coupling). The approach is typically considered valid for attached high–Reynolds–number flows, *i.e.*, for cruise. The boundary layer is divided into 3 regions as follows: (i) a laminar portion which is treated by means of the Thwaites collocation method (Ref. [10]); (ii) a transition region for which its position is calculated following the Michel semi–empirical method (Ref. [11]); (iii) a turbulent portion evaluated using the Green "lag–entrainment method" (Ref. [12]).

Coupling between integral boundary layer and potential flow is implemented following the Lighthill transpiration velocity approach (Ref. [13]). This method has a considerable advantage over the displacement thickness method since coupling is realized by adjustment of the boundary conditions only (two–dimensional strip–theory approach), as $\partial\varphi/\partial n = \mathbf{v}_{\rm B} \cdot \mathbf{n} + \chi_{\rm V}$, where

$$\chi_{\rm V} = \frac{\partial}{\partial s}(u_e\delta^*) = \frac{\partial}{\partial s}\int_0^\delta (u_e - u)\, d\eta, \tag{1}$$

used as strip theory (see Refs. [6] and [7] for details). Other contributions to the drag (such as wave drag) are currently evaluated by empirical corrections (see again Ref. [7]).

Flight Equations

For the evaluation of the angle of attack, α, and the elevator deflection, η, required during cruise flight, the following flight model has been used:

$$C_{L_{trim}} = C_{L_0} + C_{L_\alpha}\alpha + C_{L_\eta}\eta = \frac{W}{qS} \quad \text{and} \quad C_{M_{trim}} = C_{M_0} + C_{M_\alpha}\alpha + C_{M_\eta}\eta = 0, \tag{2}$$

where W is the aircraft weight for the flight condition of interest, q is the dynamic pressure and S is the reference surface; C_{L_0} and C_{M_0} are the lift and moment coefficient for both trim angle and angle of attack equal to zero; C_{L_α} and C_{M_α} are the derivatives with respect to the angle of attack while C_{L_η} and C_{M_η} are the derivatives evaluated with respect to the trim angle (for simplicity the thrust has not been taken into account).

The angle of attack and elevator deflection required for level flight are subsequently used to evaluate the induced drag approximated as $C_{D_{trim}} = C_{D_0} + k_1\alpha^2 + k_2\alpha + k_3\alpha\eta + k_4\eta + k_5\eta^2$.

The evaluation of $C_{D_{trim}}$, $C_{L_{trim}}$ and $C_{M_{trim}}$ is solved in two steps: (i) C_{L_0}, C_{M_0} and C_{D_0} are evaluated by means of a Trefftz plane theory which shows to be more accurate and less time consuming than the direct pressure integration (Ref. [14]); and (ii) C_{L_α}, C_{M_α}, C_{L_η} and C_{M_η} are approximated by central differences of C_L and C_M at α and η equal to zero. Evaluation of a single BEM model (*i.e.*, , one set of aerodynamics influence coefficients, the most expensive portion of BEM!), with five sets of boundary conditions, is sufficient to derive the five k_j coefficients.

The results from this small perturbation method proved to be in good agreement with direct evaluation, see Fig. 2.

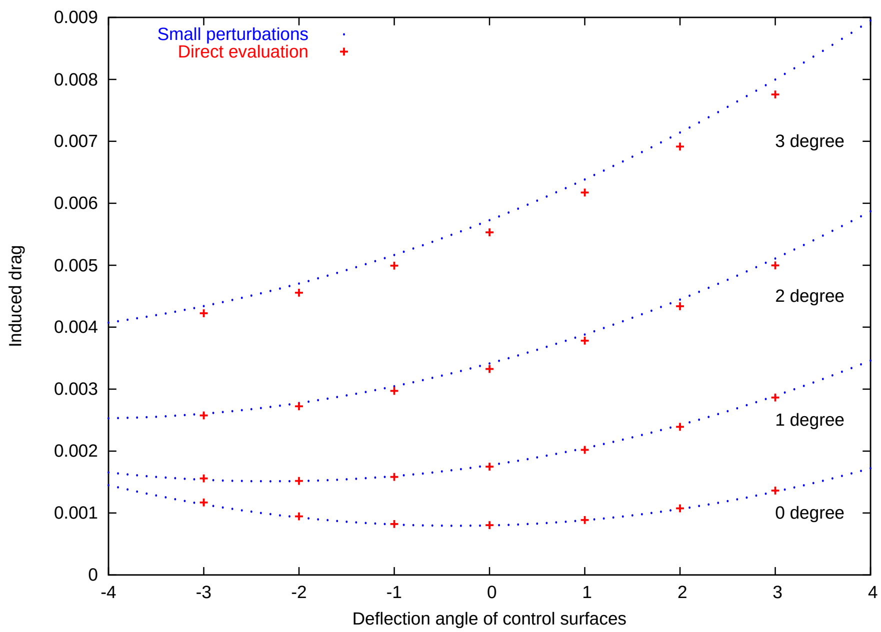


Figure 2: Comparison between direct evaluation of the induced drag and the small perturbation method for different angles of attack.

The optimization procedure

The optimization procedure is used to minimize the following objective function, a combination of structural weight W_E, fuel weight W_F and efficiency (Lift to Drag ratio) $E = L/D$:

$$OBJ = w_1 \frac{W_E}{W_{E_{ref}}} + w_2 \frac{W_F}{W_{F_{ref}}} + w_3 \frac{E_{ref}}{E} \tag{3}$$

In the objective function the ratio of the figures of merit with respect to their reference values, $W_{E_{ref}}$, $W_{F_{ref}}$ and E_{ref}, are used. The relative importance of the figures of merit is set with the weight factors (w_1, w_2 and w_3). The user can chose them in order to perform the desired type of optimization.

A set of constraints, defined in Table 2, is used to take several operational limits and structural strength limits into account. As mentioned above, an innovative sequential optimization procedure has

g_1 –	Range	$R \geq R_{ref}$
g_2 –	Fuel volume	$V_F \leq V_{F\,avail}$
g_3 –	Efficiency	$E \geq E_{ref}$
g_4 –	Normal stress	$\sigma \leq \sigma_{ref}$
g_5 –	Shear stress	$\tau \leq \tau_{ref}$
g_6 –	Fuselage volume	$V_{fus} \geq V_{fus_{ref}}$
g_7 –	Max span	$S \leq S_{ref}$
g_8 –	Angle of attack	$\alpha \leq \alpha_{ref}$
g_9 –	Angle of deflection	$\eta \leq \eta_{ref}$
g_{10} –	Stability	$C_{M_\alpha} \leq C_{M_{\alpha ref}}$
g_{11} –	Flutter speed	$U_F \geq U_{F_{ref}}$

Table 2: Available constraints

been introduced to avoid convergence issues. Specifically, the procedure involves a sequence of three sub–optimizations (*i.e.*, optimizations with a reduced number of design parameters or disciplines). The first sub–optimization is focused on improving the configuration in terms of performance (L/D) and satisfying all the violated constraints, except the aeroelastic one. In the second sub–optimization (structural) the objective function is the aircraft empty weight and the aeroelastic constraint is considered. This involves almost exclusively structural variables (in addition, two configuration variables are used: the fuselage profile curvature X_1 and wing relative position to the fuselage X_4; they have been used in this structural optimization because they are effective in terms of mass balancing without influencing the aircraft weight; they are necessary since the aircraft must be balanced while the weight decrease). The third sub–optimization is focused only on balancing the aircraft exactly at mid–cruise in order to minimize the trim loss over all the cruise. Because of this, the objective is different from the previous one. In this case it is defined as a function of the trim angle ($OBJ_3 = |\eta/\eta_{ref}|$).

In summary, we have

- First sub–optimization:
  - an objective function composed as a combination of structural weight, fuel weight and efficiency is used ($w_1 = 0.25$, $w_2 = 0.25$ and $w_3 = 0.5$);

  - all variables, 19 structural and 17 geometric are active;
  - all constraints are active except the aeroelastic constraint.

- Second sub–optimization:
  - an objective function composed as a combination of structural weight, and fuel weight is used ($w_1 = 0.7$, $w_2 = 0.3$ and $w_3 = 0$);
  - 19 structural and only 2 geometric variables (X_1 and X_4) are active;
  - all constraints are active except the geometric constraints (g_6 and g_7).

- Third sub–optimization:
  - an objective function composed with the aircraft trim angle is used;
  - only the 2 geometric variables afore–mentioned are active;
  - only constraints on flight mechanics and performance are active (g_1, g_3, g_8, g_9 and g_{10}).

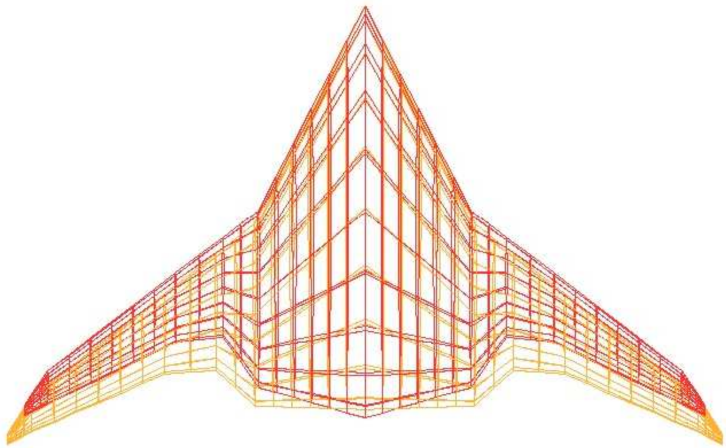
Comparison between final and initial configuration

Comparison between initial, target and optimized configurations are shown in Tab. 3. As can be seen, the initial configuration is far from satisfying the requirements specified from the target configuration. Large differences in weight, as well as in efficiency, are noticed, so that five of the eleven constraints are violated. However, the optimization procedure improved the design and the final optimized configuration fulfills the design targets.

	baseline	optimized	target
Gross weight (ton)	400	356	370
Empty weight (ton)	183	151	150
Fuel weight (ton)	130	117	130
Lift coefficient	0.217	0.208	
Range (nm)	4600	5142	5000
Angle of attack – mid cruise	3.7^0	2.47^0	$< 3.5^0$
Trim angle – mid cruise	-2.33^0	$-1.610^{-3\,0}$	0^0
Efficiency	15.9	17.8	> 17
Pitch moment derivative	$-1.381\ 10^{-2}$	$-5.4\ 10^{-3}$	$-5.\ 10^{-3}$
Flutter speed (m/s)	235	> 350	> 350
Payload surface (m^2)	585	570	570
Wetted surface (m^2)	1405	1299	

Table 3: Comparison between initial and final configuration

Figure 3 shows in planform a comparison between the initial and the final configurations. A change in fuselage profile curvature X_1 is also noticed but it cannot be seen from this view. The improvements obtained with respect to the initial configuration for some important figures of merit are given as well. The percentages show that an appreciable improvement is achieved in terms of weight and efficiency.



Gross weight	-11.2%	Empty weight	-17.5%
Fuel weight	-10%	Efficiency	+ 11.9%

Figure 3: Comparison between optimized (dark) configuration and initial configuration

Concluding remarks

It is important to note that, as stated above, this sequential procedure was introduced as a way to determine a good initial guess (that is, an initial guess sufficiently accurate to insure convergence), for the standard approach, *i.e.*, for the complete multidisciplinary optimization (the same that was attempted, without success, at the beginning of the project). Thus, the result of this sequence of sub–optimizations was subsequently used as the initial guess for the standard approach. The results obtained with the standard approach using this initial guess are virtually identical to those obtained after third sub–optimization. Thus, it appears that the above procedure may be considered as a powerful alternative to the standard approach. However, a considerable number of additional applications ought to be considered before arriving at the final conclusions. In any event, the approach proposed appears very useful to identify a very good estimate of the initial guess.

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