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Toward Wing Aerostructural Optimization Using Simultaneous Analysis and Design Strategy

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The application and computational efficiency of wing aerostructural optimization using simultaneous analysis and design (SAND) strategy is investigated. A coupled adjoint aerostructural analysis method based on quasi-three-dimensional aerodynamic analysis is used for this research. Two different optimization problems are tested. In the first case a wing aeroelastic optimization is performed using both nested analysis and design (NAND) and SAND strategies. In this optimization the wing box structure is optimized to achieve minimum wing weight. In the second optimization the wing structure as well as the outer aerodynamic shape are optimized to achieve minimum aircraft fuel weight. The results of both SAND and NAND optimizations have been compared based on accuracy and computational cost.

I. Introduction

A multidisciplinary design optimization (MDO) problem can be formulated using different strategies. The MDO strategies determine how different disciplines are connected to each other and how the optimization problem should be solved. Different monolithic as well as distributed MDO strategies have been developed.¹ Selection of the MDO strategy for an MDO problem is a challenge. Some strategies make the analysis easier but the optimization more difficult, and some do the opposite. Some authors tried to benchmark different MDO strategies using simple test problems.²⁻⁴ However the efficiency of an MDO strategy is strongly affected by the nature of the problem.

Tedford and Martins² applied multidisciplinary feasible, individual discipline feasible, simultaneous analysis and design, collaborative optimization and concurrent subspace optimization to a couple of test cases and concluded that SAND is the most efficient method in terms of computational cost.

In general an optimization problem can be solved in two ways. The first approach is called nested analysis and design (NAND). In this approach the solvers, which can be complex PDE solvers such as CFD or FEM codes, are treated as black boxes. It means that the state variables are computed implicitly based on the design variables. In other words, for each optimization iteration, first the converged values of the state variables are computed using the design variables, then the value of the objective function is evaluated based on the design variables and the converged values of the state variables. This approach makes the optimization *safer*, since a premature solution is feasible.

The alternative of NAND is simultaneous analysis and design (SAND). In this approach the state variables are computed in the same iterations for finding the optimum values of the design variables. Theoretically SAND is computationally more efficient than NAND, since there is no need to find a converged values of the state variables at each iteration. Only the residuals are needed. However the application of SAND faces some difficulties.

SAND formulation results in an increase in the total number of the design variables and constraints. Using high fidelity CFD or FEM with thousands or even millions of state variables makes the implementation of SAND computationally prohibitive. Orozco and Ghattas⁵ suggested a reduced SAND method, in which

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the dimension of the problem is extensively reduced to make SAND implementation possible. Examples of application of the reduced SAND method to aerodynamic and structural optimization can be found in references.^{6,7} The large number of design variables and constraints may negatively affect the computational aspects of SAND. Although each iteration in SAND is faster than NAND since the multidisciplinary feasibility is not required, due to the large number of design variables the optimization may need more iterations to converge so the total optimization time may not be necessarily shorter. Besides the sensitivity analysis in SAND can be more expensive than NAND again due to the large number of design variables and constraints. On the other hand, in the NAND approach, the discipline convergence can be achieved by the use of e.g. Newton method. In SAND usually the quasi-Newton methods such as BFGS are used, which are less efficient than the Newton method, which negatively affects the rate of convergence in a SAND optimization.

In this paper a comparison between NAND and SAND methods for wing aerostructural optimization is presented. Two different optimization problems are considered. The first one is an aeroelastic optimization, in which the design variables are only the wingbox structure parameters. The second one is a full aerostructural optimization, where the wing planform and airfoil shape as well as the wing box structure are optimized together. Both problems are solved using NAND and SAND and the efficiency of the optimization in terms of the optimum found by the methods and the computational time are discussed at the end of the paper.

II. Simultaneous analysis and design optimization

A multidisciplinary optimization using the NAND method is formulated as follows:

$$\begin{aligned}
 \min \quad & f(x, y(x, y)) \\
 \text{w.r.t.} \quad & x \\
 \text{s.t.} \quad & h(x, y(x, y)) = 0 \\
 & c(x, y(x, y)) \leq 0
 \end{aligned} \tag{1}$$

where f is the objective function, h and c are the equality and inequality constraints respectively. x is the vector of design variables and y is the vector of coupling variables. For more detailed description one can refer to.¹

The same problem can be formulated using the SAND method as follows:

$$\begin{aligned}
 \min \quad & f(x, \bar{y}, w) \\
 \text{w.r.t.} \quad & x, \bar{y}, w \\
 \text{s.t.} \quad & h(x, \bar{y}, w) = 0 \\
 & c(x, \bar{y}, w) \leq 0 \\
 & c_c = y - \bar{y} = 0 \\
 & R(x, \bar{y}, w) = 0
 \end{aligned} \tag{2}$$

In this formulation in addition to the original design variables, x , the surrogate values of the coupling variables, \bar{y} , and the state variables w are added to the design vector. In addition to the original constraint of the problem, a series of consistency constraints c_c are added to make sure the actual values of the coupling variables are the same as the surrogate values of the coupling variables at the end of the optimization. Eventually the residuals of the system R are defined as equality constraints.

III. Wing aerostructural analysis

The method presented by Elham and van Tooren⁸ is used for wing aerostructural analysis. This method is based on a Quasi-Three-Dimensional (Q3D) aerodynamic analysis method which reduces the number of state variables dramatically compared to a full 3D CFD analysis. In the method presented in⁸ the wing drag is predicted using a Q3D aerodynamic analysis and the wing structural deformation and structural failure criteria are predicted using a finite beam element model. In a Q3D approach the viscous compressible drag of a wing can be computed by a combined use of an inviscid 3D solver, a vortex lattice method (VLM) in this case, and a viscous 2D solver. In such an approach, a VLM is used to compute the wing spanwise lift

distribution and to compute the wing induced drag using Trefftz plane analysis. The 2D airfoil analysis is executed to compute the parasite drag of the several wing sections along the span. Integrating the parasite drag over the span and adding it to the induced drag computed by the VLM, the wing total drag is computed. In order to analyze 2D airfoils, the effective flow properties, such as Mach number and Reynolds number, and the effective angle of attack at each section need to be determined. The effective flow properties are computed using the free stream flow properties corrected based on the sweep theory and the local downwash angle. The effective angle of attack is determined based on the wing global angle of attack, the local geometrical twist and the downwash angle. More details of the method are presented in reference.⁸ In this method four governing equations should be satisfied:

$$R_1(X, \Gamma, U, \alpha) = AIC(X, U) \Gamma - RHS(X, U, \alpha) = 0 \quad (3)$$

$$R_2(X, \Gamma, U) = K(X)U - F(X, \Gamma) = 0 \quad (4)$$

$$R_3(X, \Gamma) = L(X, \Gamma) - nW_{des} = 0 \quad (5)$$

$$R_4(X, \Gamma, U, \alpha, \alpha_i) = C_{l_{visc}}(X, U, \alpha, \alpha_i) - C_{l_{invisc}}(X, \Gamma) = 0 \quad (6)$$

The first and the second equations are the governing equations of the aerodynamic (VLM) and the structure respectively. The third equation is needed to find the proper angle of attack to make the wing total lift equal to the design weight multiplied by the load factor. The fourth equation is related to the Q3D analysis. It forces the viscous and inviscid analysis to be consistent, i.e. the airfoil lift at each section computed by the 2D analysis should be equal to the lift computed by the VLM corrected based on the wing sweep. The state variables in this case are the vorticity Γ , the displacements u , the wing angle of attack α and the downwash angles α_i .

If an aeroelastic analysis and optimization is considered instead of an aerostructural analysis, where the wing shape optimization for minimum drag is not considered, the fourth governing equation (R_4) can be eliminated. In such a case 2D airfoil analysis will not be executed and only the VLM and finite element models are coupled to each other.

Elham and van Tooren⁸ developed a tool, named FEMWET, based on the proposed method. The inputs of FEMWET are the wing planform and airfoil geometry (parametrized using the Chebychev polynomials) and the thickness of the wingbox structure in several spanwise sections. The outputs are the wing drag, structural weight and failure values, defined as the ratio of the applied stress to the maximum allowable stress in each structural element. The structural failure due to material yield as well as the Euler buckling and the shear buckling are considered.

FEMWET uses the Newton method to solve the coupled system as follows:

$$\underbrace{\begin{bmatrix} \frac{\partial R_1}{\partial \Gamma} & \frac{\partial R_1}{\partial U} & \frac{\partial R_1}{\partial \alpha} & \frac{\partial R_1}{\partial \alpha_i} \\ \frac{\partial R_2}{\partial \Gamma} & \frac{\partial R_2}{\partial U} & \frac{\partial R_2}{\partial \alpha} & \frac{\partial R_2}{\partial \alpha_i} \\ \frac{\partial R_3}{\partial \Gamma} & \frac{\partial R_3}{\partial U} & \frac{\partial R_3}{\partial \alpha} & \frac{\partial R_3}{\partial \alpha_i} \\ \frac{\partial R_4}{\partial \Gamma} & \frac{\partial R_4}{\partial U} & \frac{\partial R_4}{\partial \alpha} & \frac{\partial R_4}{\partial \alpha_i} \end{bmatrix}}_J \begin{bmatrix} \Delta \Gamma \\ \Delta U \\ \Delta \alpha \\ \Delta \alpha_i \end{bmatrix} = - \begin{bmatrix} R_1(X, \Gamma, U, \alpha) \\ R_2(X, \Gamma, U) \\ R_3(X, \Gamma) \\ R_4(X, \Gamma, U, \alpha, \alpha_i) \end{bmatrix} \quad (7)$$

The Jacobian matrix, J in (7), is also used to compute the derivatives of any function of interest I , for example the wing drag, with respect to the design variables, for example the wing span using the coupled adjoint method as follows:

$$\frac{dI}{dx} = \frac{\partial I}{\partial x} - \lambda_1^T \left(\frac{\partial R_1}{\partial x} \right) - \lambda_2^T \left(\frac{\partial R_2}{\partial x} \right) - \lambda_3^T \left(\frac{\partial R_3}{\partial x} \right) - \lambda_4^T \left(\frac{\partial R_4}{\partial x} \right) \quad (8)$$

where the adjoint vector λ is calculated as follows:

$$\begin{bmatrix} \frac{\partial R_1}{\partial \Gamma} & \frac{\partial R_1}{\partial U} & \frac{\partial R_1}{\partial \alpha} & \frac{\partial R_1}{\partial \alpha_i} \\ \frac{\partial R_2}{\partial \Gamma} & \frac{\partial R_2}{\partial U} & \frac{\partial R_2}{\partial \alpha} & \frac{\partial R_2}{\partial \alpha_i} \\ \frac{\partial R_3}{\partial \Gamma} & \frac{\partial R_3}{\partial U} & \frac{\partial R_3}{\partial \alpha} & \frac{\partial R_3}{\partial \alpha_i} \\ \frac{\partial R_4}{\partial \Gamma} & \frac{\partial R_4}{\partial U} & \frac{\partial R_4}{\partial \alpha} & \frac{\partial R_4}{\partial \alpha_i} \end{bmatrix}^T \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \end{bmatrix} = \begin{bmatrix} \frac{\partial I}{\partial \Gamma} \\ \frac{\partial I}{\partial U} \\ \frac{\partial I}{\partial \alpha} \\ \frac{\partial I}{\partial \alpha_i} \end{bmatrix} \quad (9)$$

The partial derivatives required in Eqs. (8) and (9) are computed using automatic differentiation. More details are presented in.⁸

FEMWET can also compute the value of the aileron effectiveness, which is defined as the ratio of elastic to rigid roll moment of the wing due to an aileron deflection, and its derivative with respect to the design variables. The minimum value of the aileron effectiveness is an important constraint in a wing aeroelastic as well as aerostructural optimization.¹¹

The results of FEMWET for wing drag estimation, wing structural deformation and weight prediction are validated by comparing the results with the results of higher fidelity analysis as well as the experimental results. Besides, the accuracy of sensitivity analysis is verified by the use of finite differencing. Details of FEMWET validation is presented in.⁸ Figure 1 shows the Fokker 100 wing drag predicted by FEMWET compared to the MATRICS-V,⁹ a high fidelity 3D CFD code. The drag analysis is performed for the Fokker 100 cruise condition. Figure 2 compared the actual structural twist of A320 wing under 1g load (presented in¹⁰) to the results of FEMWET.

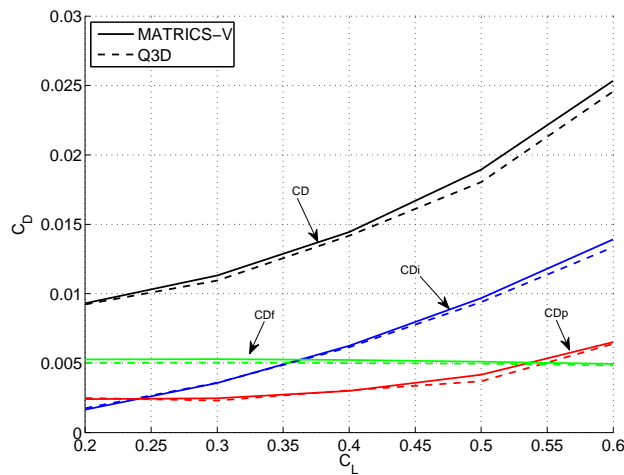


Figure 1: Comparison of computed drag by the MATRICS-V and Q-3D solvers for cruise condition (1g loaded wing and $M = 0.75$).⁸

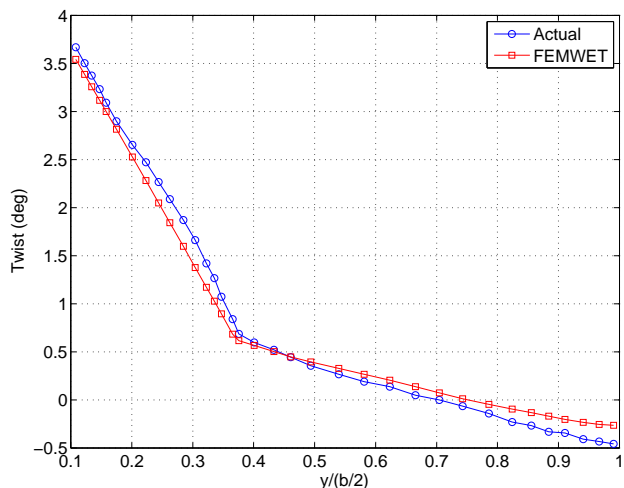


Figure 2: A320-200 wing twist under 1g load.⁸

In an optimization using SAND the Newton iteration is not required. All the state variables are defined as design variables and the analysis is done only to compute the value of the residuals (R_1 to R_4) and the derivative of them with respect to the design variables, which are in this case all the original design variables x and the state variables. In this research the FEMWET code is modified to be used in SAND.

IV. Wing aerolastic optimization

In the first step a wing aeroelastic optimization is considered. In such an optimization the wingbox structure is optimized for wing minimum weight under the effect of aerodynamic loads. The wing airfoil and planform shape are kept fixed during the optimization. In a NAND approach this optimization is formulated as follows:

$$\begin{aligned}
 \min \quad & W_w \\
 \text{w.r.t.} \quad & x \\
 \text{s.t.} \quad & F_k \leq 0 \\
 & \frac{L_{\delta_0}}{L_{\delta}} - 1 \leq 0
 \end{aligned} \tag{10}$$

where W_w is the wing structural weight, x is the design vector including the thickness of the wingbox structure along the span, F_k are the structure failure constraints, L_{δ} is the derivative of the wing rolling moment L with respect to the aileron deflection angle δ . Subscript 0 means the initial aircraft. So the last constraint ensures that the aileron defectiveness of the new wing is not lower than the aileron effectiveness of the initial wing. In the NAND optimization the original FEMWET code is used to compute the values of the objective function and the constraints based on the converged values of the state variables.

The Airbus A320 wing is used as the test case for this optimization. Figure 3 shows the wing planform geometry and Table 1 summarizes the load cases used for the optimization.

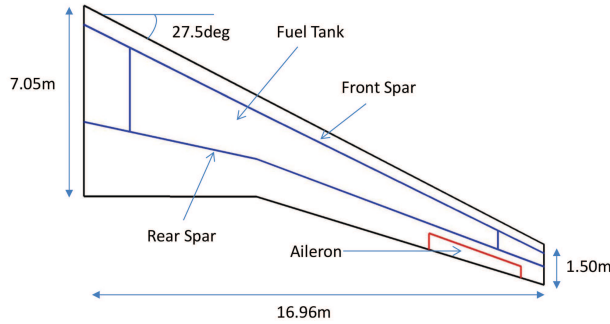


Figure 3: Initial planform geometry of the wing used for aeroelastic optimization.

Table 1: Load cases for wing aerostructural optimization.

Load case	type	aircraft weight	H [m]	M	n [g]	q [Pa]
1	pull up	MTOW	7500	0.89	2.5	21200
2	pull up	MTOW	0	0.58	2.5	23900
3	push over	MTOW	7500	0.89	-1	21200
4	gust	ZFW	7500	0.89	1.3	21200
5	roll	W_{des}	4000	0.83	1	29700

Load cases 1 to 3 in Table 1 are used to compute the failure constraints due to material yield and buckling. Load case number 4 is used to compute the failure due to fatigue. As suggested by Hurlimann¹² the effect of fatigue can be taken into account by limiting the stress in the wing lower panel to 42% of the maximum allowable stress in a 1.3g gust load case. The last load case is used to compute the aileron effectiveness. In total 642 constraints on structural failure and one constraint on aileron effectiveness are used.

The same optimization can be formulated using SAND approach as follows:

$$\begin{aligned}
& \min && W_{wing} \\
& w.r.t. && x, w \\
& s.t. && F_k \leq 0 \\
& && \frac{L_{\delta_0}}{L_{\delta}} - 1 \leq 0 \\
& && R(x, w) = 0
\end{aligned} \tag{11}$$

In this approach the design vector includes both the wingbox structure thickness variables x and the state variables w , that includes the values of Γ , u , and α . As mentioned earlier in an aeroelastic optimization, 2D airfoil analysis and consequently R_4 in Eq. (6) are not required. So α_i is not considered as a state variable. The constraints on structural failure and aileron effectiveness are used in SAND as well. New constraints are added to satisfy the governing equations, i.e. $R = 0$.

Since the aeroelastic analysis should be performed for 5 different load cases, the values of the state variables for all these load cases are defined as surrogate variables. So the length of w is five times of the length of the vector of the state variables. In total 993 design variables are used, where 40 of them are the original design variables x , and 953 are the surrogate variables w . Similarly 953 constraints on R are defined. It should be noted that for u only the free degrees of freedom are defined as surrogate variable. The SNOPT optimization algorithm¹³ is used as the optimizer. The history of NAND and SAND optimization are shown in Figs. 4 and 5 respectively.

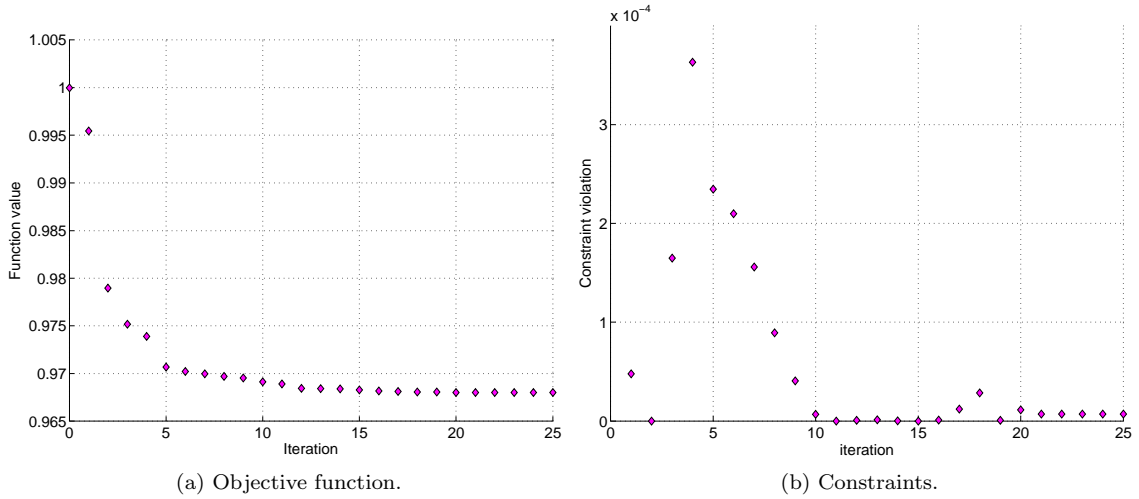


Figure 4: History of optimization using NAND strategy.

Table 2 summarizes the results of both NAND and SAND optimization. From this table one can find that both NAND and SAND optimizations were converged to almost the same optimum wing structural weight. However despite the expectation, the SAND optimization took longer time to converge. Each function evaluation in NAND (including analysis of 5 load cases in parallel) takes 5.67 second, while the same analysis using SAND takes 2.46 seconds. In analysis SAND is more than twice faster. However when the sensitivities are required NAND performs better. The same function evaluation but including sensitivity analysis (adjoint and automatic differentiation) takes 38.06 seconds using NAND, while 51.92 seconds using SAND. The reason is that the total number of design variables and constraints in SAND is much larger than NAND. In NAND 40 design variables, one objective function and 643 constraints on structural failure and aileron effectiveness are defined. So in total 25760 (40×644) derivatives should be computed. However in SAND 993 design variables, one objective function and $643 + 953 = 1596$ constraints are used. So in total 1584828 derivatives should be computed. It makes the sensitivity analysis computationally more expensive than NAND. The higher cost of sensitivity analysis at the end compensates the advantage of SAND in faster function evaluation.

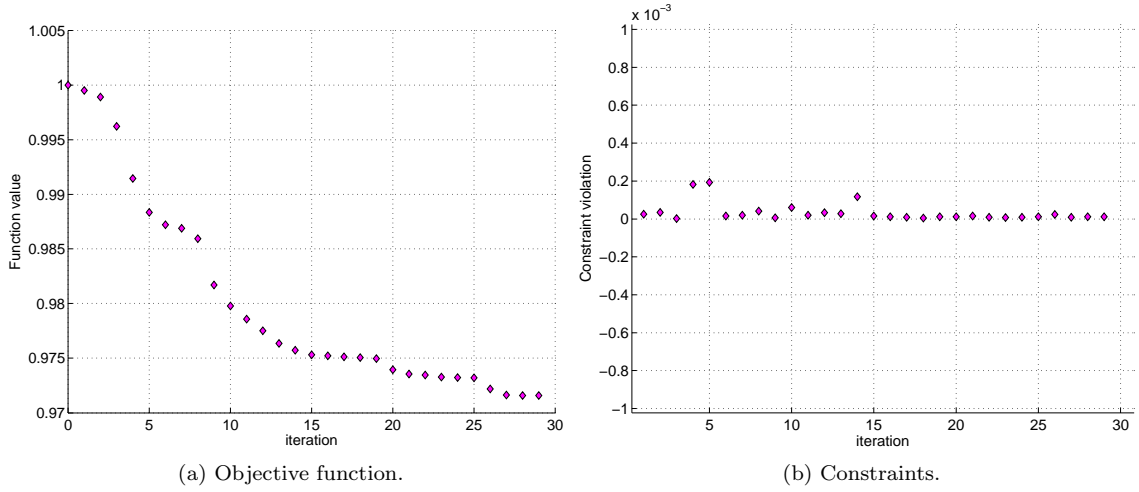


Figure 5: History of optimization using SAND strategy.

Table 2: Results of aeroelastic optimization.

Strategy	Objective function	Constraint violation	No. iteration	No. function evaluation	total time
NAND	0.9680	6.99×10^{-6}	25	135	1
SAND	0.9716	1.11×10^{-5}	29	112	1.085

V. Wing aerostructural optimization

A full wing aerostructural optimization using NAND can be formulated as follows:

$$\begin{aligned}
 \min \quad & W_f \\
 \text{w.r.t.} \quad & x \\
 \text{s.t.} \quad & \text{Failure}_k - \text{Failure}_{max} \leq 0 \quad k = 1..642 \\
 & \frac{L_{\delta_0}}{L_{\delta}} - 1 \leq 0 \\
 & \frac{MTOW/S_w}{MTOW_0/S_{w_0}} - 1 \leq 0 \\
 & \frac{V_f}{V_{f_{available}}} - 1 = 0
 \end{aligned} \tag{12}$$

In such an optimization the aircraft fuel weight is defined as the objective function. In addition to the wing box structure thickness, the design vector x also includes the wing planform variables and the airfoil variables. The planform is parametrized using 6 variables: span, root chord, taper ratio, leading edge sweep, twist angle at the kink position and twist angle at tip. In addition to the planform geometry the wing airfoil geometry at 8 spanwise positions are defined as design variables. The airfoil geometry is parametrized using Chebyshev polynomials. The Chebyshev polynomials, g_i , are defined as:

$$g_j(x) = \cos(j \cos^{-1}(x)) \tag{13}$$

Using the Chebyshev polynomials the original airfoil shape is perturbed as:

$$\Delta n(s) = \sum_{j=1}^J G_j g_j(s) \tag{14}$$

where Δn is the airfoil perturbation normal to its current surface, s is the fractional arc length of each side of the airfoil and G_j are the mode amplitudes, that are defined as design variables. Each airfoil section is parametrized using 20 modes, so 160 design variables are used in total for wing airfoil shape.

The first two constraints in Eq. (12) are the same as the aeroelastic optimization. However two new constraints are defined in this problem. A constraint is defined to make sure the wing loading (maximum take off weight divided by wing area S_w) is not higher than the initial wing loading. This constraint is required to make sure the aircraft can satisfy the take off and landing performance. Another constraint is added to make sure the available fuel tank volume is enough to store all the required fuel.

The aerostructural optimization problem in Eq. (12) can be formulated using SAND strategy as follows:

$$\begin{aligned}
\min \quad & \overline{W}_f \\
\text{w.r.t.} \quad & x, w, \overline{W}_f, \overline{MTOW} \\
\text{s.t.} \quad & \text{Failure}_k - \text{Failure}_{max} \leq 0 \quad k = 1..642 \\
& \frac{L_{\delta_0}}{L_\delta} - 1 \leq 0 \\
& \frac{MTOW/S_w}{MTOW_0/S_{w_0}} - 1 \leq 0 \\
& \frac{V_f}{V_{f_{available}}} - 1 = 0 \\
& \frac{\overline{W}_f}{W_f} - 1 = 0 \\
& \frac{MTOW}{\overline{MTOW}} - 1 = 0 \\
& R(x, w, \overline{W}_f, \overline{MTOW}) = 0
\end{aligned} \tag{15}$$

In this formulation all the state variables are defined as surrogate variables. Besides two surrogates variables for fuel weight and MTOW are used. The state variables include Γ, u, α and α_i for the five load cases shown in Table 1 as well as the cruise condition. In total 993 design variables are used: 40 for wing box structure, 8 for planform geometry, 160 for airfoils geometry, 785 for w and two for \overline{W}_f and \overline{MTOW} . In addition to the initial 645 constraints on structural failure, aileron effectiveness, fuel tank volume and wing loading, 785 constraints are defined on the residuals. So in total 1430 constraints are used.

Table 3 summarizes the results of both NAND and SAND optimizations. From this table one can observe that SAND could not achieve the same optimum as NAND, however the computational cost of SAND was extremely lower than NAND. Each function evaluation in NAND takes 155 seconds, while each function evaluation in SAND is just 21 seconds. Despite the aeroelastic optimization, where the cost of gradient computation in SAND was higher than NAND, in aerostructural optimization the gradient computation in NAND takes 217 second and in SAND 116 second. However these numbers are only for the initial design vector. During the optimization the computational cost can change by a large value. Different airfoil shapes need different number of CFD iteration to converge. Besides different design vectors need different number of Newton iteration to converge. The experience showed that getting closer to the optimum the time required for each function evaluation in NAND increases by a larger factor comparing to SAND. The reason is that in SAND no Newton iteration is applied so the change in computational time is only due to change in number of required CFD iteration for airfoil analysis. However in NAND the number of CFD iterations is multiplied by the number of Newton iterations.

Table 3: Results of aerostructural optimization.

Strategy	Objective function	Constraint violation	No. iteration	No. function evaluation	total time
NAND	0.9045	4.9×10^{-6}	39	271	1
SAND	0.9391	3.0×10^{-5}	44	148	0.13

The history of optimization of both NAND and SAND are plotted in Figs. 6 and 7 respectively.

Figure 8 shows the planform shape of the initial wing as well as optimized wings using NAND and SAND

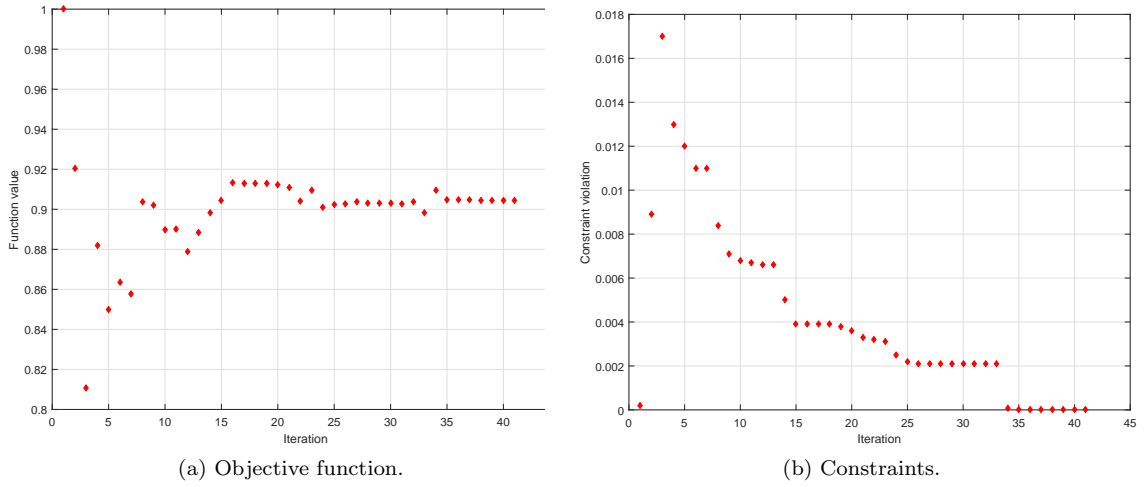


Figure 6: History of optimization using NAND strategy.

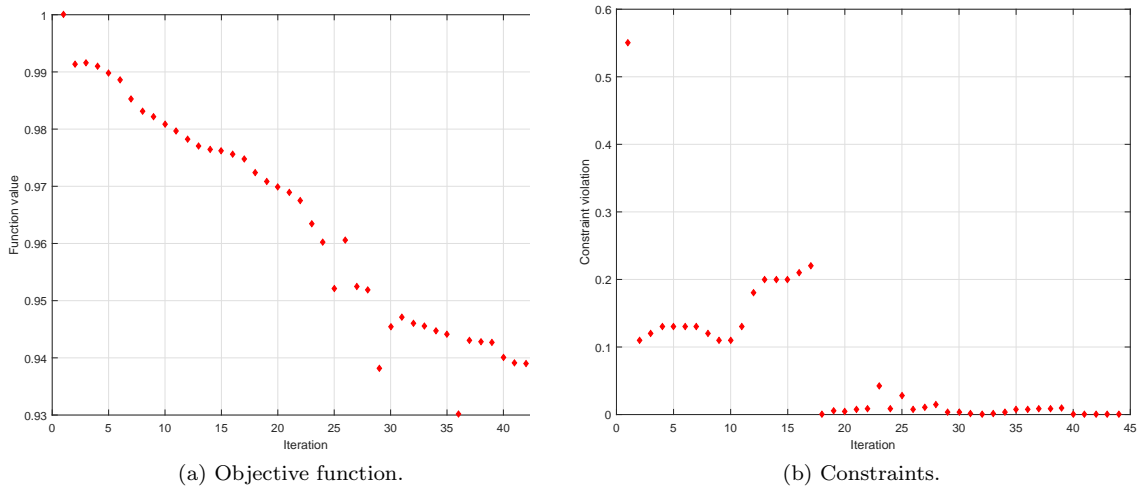


Figure 7: History of optimization using SAND strategy.

strategies. The airfoil shapes and the pressure distribution over the airfoils are plotted in Figs. 9 and 10 respectively.

From Fig. 10 it can be seen that both NAND and SAND managed to eliminate the shock wave from the airfoils upper surfaces. However from Fig.8 it can be concluded that the main reason for getting different objective function values (aircraft fuel weight) in NAND and SAND optimization is the difference in the wing planform geometry. The output of NAND optimization has lower sweep angle and higher span. This results in lower induced drag and lower wing weight. The SAND optimization could not reduce the sweep and increase the span as much as the NAND optimization. The reason could be the high sensitivity of the residuals with respect to the wing planform parameters. A small change in those parameters can cause the large increase in the residuals. So to be able to satisfy the equality constraints on residuals the optimizer did not change the planform shape as much as the NAND optimization. However a proper scaling can lead to better results.

VI. Conclusions

The computational efficiency of wing aerostructural optimization using SAND strategy has been investigated. The main difficulties in applying SAND for high fidelity aerostructural optimization is the large

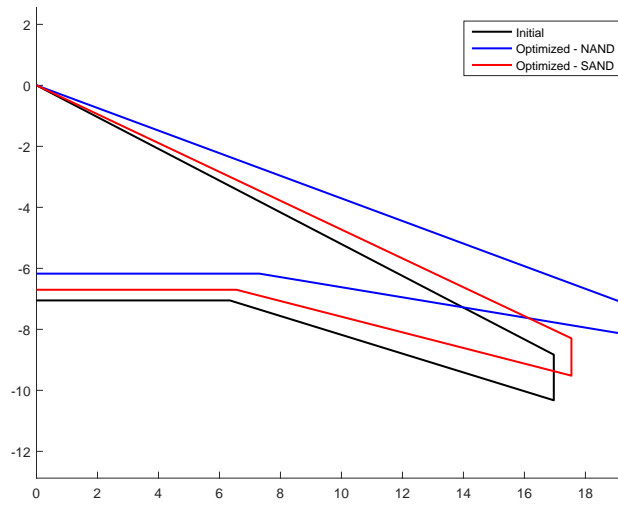


Figure 8: Planform geometry of the Initial and the optimized wings.

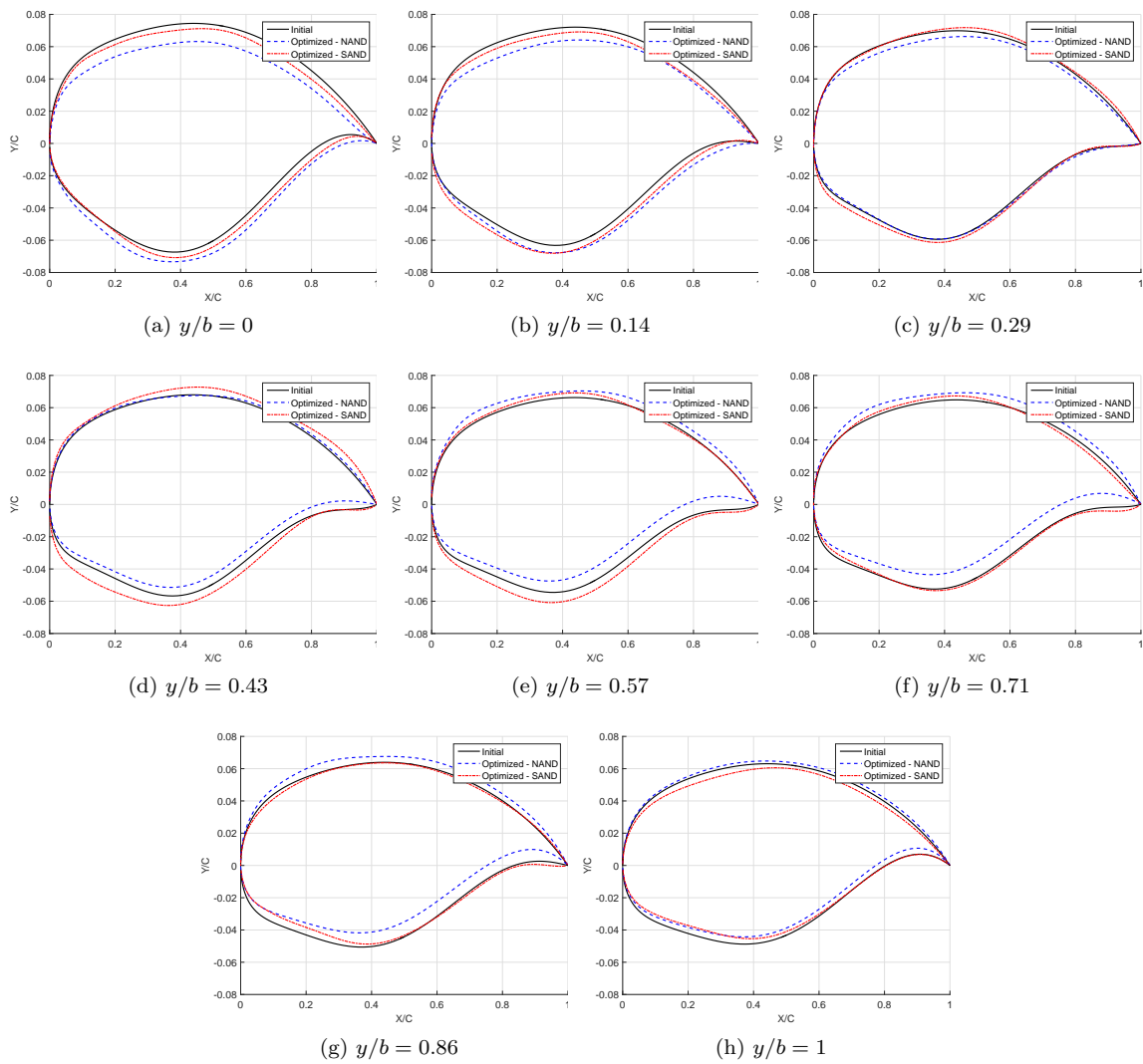


Figure 9: The shape of the airfoils is several spanwise positions.

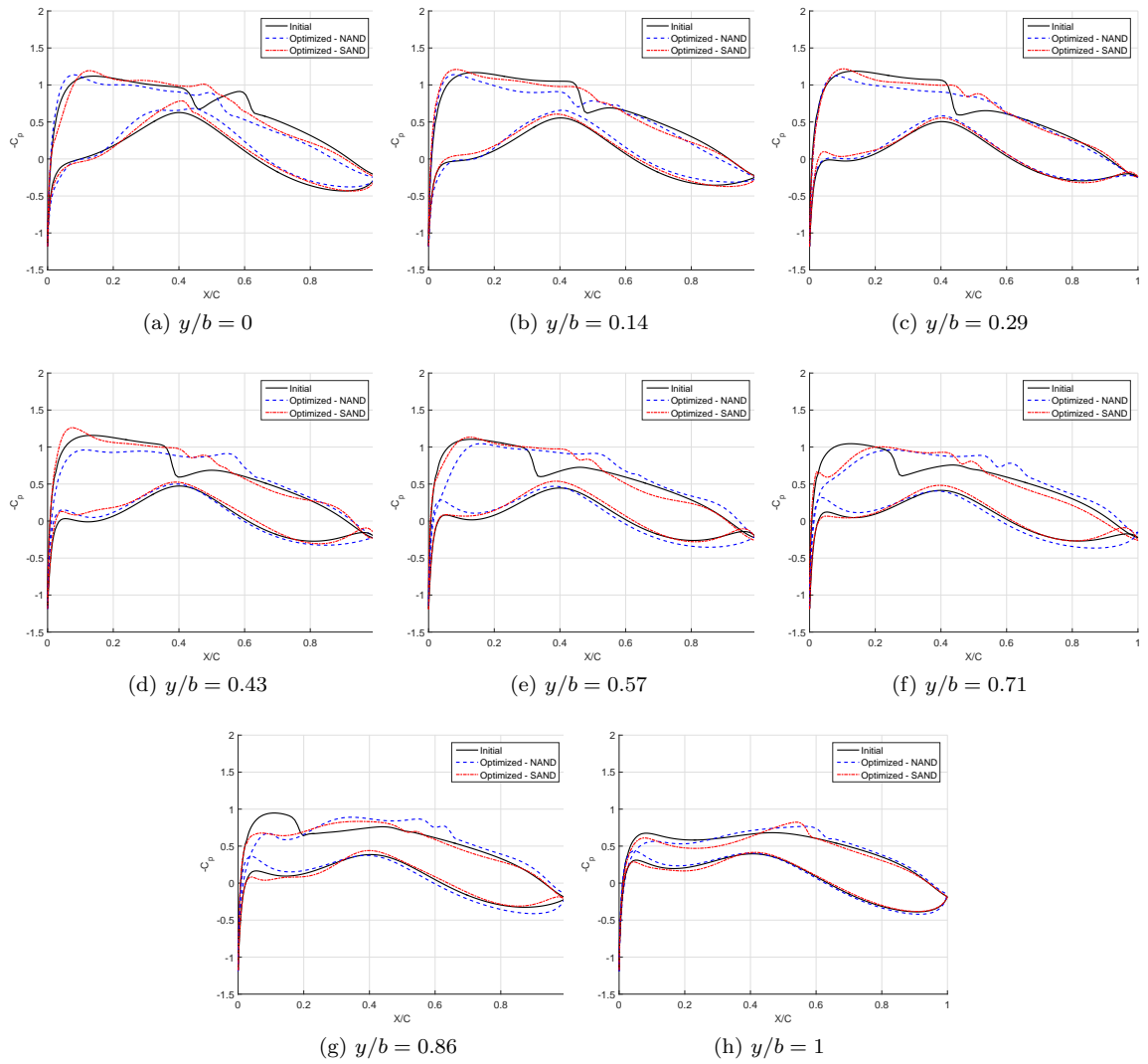


Figure 10: Pressure distribution on airfoils in several spanwise positions.

number of design variables. In this research a quasi-three-dimensional aerodynamic analysis method was used, which reduces the number of aerodynamic state variables compared to three dimensional CFD analysis. Using this approach the application of SAND has been realized.

Two different optimizations have been tested. In the first case a wing aeroelastic optimization was performed, where the wing weight was minimized by optimizing the wing box structure under various load cases. Both NAND and SAND optimizations resulted in almost the same optimum point. However despite the expectations, the computational time of SAND was slightly higher than NAND. The reason was the high computational cost of sensitivity analysis in SAND. Although the computational time of analysis in SAND is lower than NAND because no convergence is required in each iteration, the large number of design variables and constraints in SAND makes the sensitivity analysis more expensive than NAND. The higher cost of sensitivity analysis in SAND compensated the lower computational cost of function evaluation at the end.

In the second case a full wing aerostructural optimization has been investigated. Both NAND and SAND strategies were used to optimize the wing structure, planform geometry and airfoil shape to minimize the aircraft mission fuel weight. The NAND optimization resulted in a better optimum, however with much higher computational cost. In a full aerostructural analysis the computational cost of SAND was lower than NAND even including sensitivity analysis.

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