

Introduction of full flight dynamic stability constraints in aircraft multidisciplinary optimization

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ABSTRACT

Obtaining satisfactory flight dynamic characteristics for an aircraft within the design process is a mandatory task required by the flight law regulations. In the classical approach dynamic stability analyses are done at the end of the design process, when most aircraft properties are already known. Possible changes of the dynamic properties can influence the whole project and force a redesign. This reason has caused a number of researchers and industry representatives to try to incorporate the dynamic analysis earlier in the design process. This demanding task has often been executed with a number of simplifications, limited to a single wing or analysis of only the longitudinal flight dynamic stability modes. The new presented approach goes much further. The article presents a successful attempt to include all dynamic modes of motion (longitudinal and lateral) into the analysis taking stability criteria as constraints. The numerical optimization process is fully automated and based on parallel processing, making the computations very efficient. Moreover, a complete aircraft in an innovative boxwing configuration is optimized with the dynamic stability constraints, which has not been achieved ever before.

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1. Introduction

Thanks to the constantly increasing computational power, numerical optimization has become more and more common in research and industrial practices. Coupling aerodynamics and structural analyses in a multidisciplinary optimization framework is a well known practice [1]. In addition to the aerodynamics and structural analyses, the analysis of flight dynamics properties of an aircraft are one of the most important ones. Although flight dynamic analyses are crucial, they are often implemented at the end of the design process because of the computational cost and complexity. Advancing towards more competitive aerospace products, comprehensive knowledge about the most important airplane characteristics is essential.

It means, that also flight dynamics characteristics should also be predicted in the early stage of design. The problem was considered among others within the SimSAC project [2]. The claim is also recognized by industry. Bazile et al. from the Airbus company describe the analytical method for Dutch Roll prediction [3]. However, more competitive designs also mean innovative, unconventional configurations, which are not well known and the classical

methods of analysis could be insufficient, especially when the configuration is strongly aerodynamically coupled. For example, Bras et al. computed flight dynamic characteristics for different configurations of an aircraft without a vertical tail [4]. The problems with flying qualities of other unconventional configurations, three surface aircraft (TSA) and tandem wing configuration, are presented also in [5,6]. Numerical optimization is proposed here to predict the properties of flight dynamics and impose stability constraints during the design process. Morris et al. presents an optimization framework for multidisciplinary optimization of supersonic tailless aircraft [7]. Static stability, as well as dynamic stability is analyzed in that work, but only for the longitudinal modes. Moreover, aerodynamic coefficients for the dynamic analyses are derived from the Digital DATCOM [8] method. Mader and Martins wrote a number of articles (e.g. [9]) about using stability constraints in aerodynamic shape optimization of a flying wing configuration. They utilized the Euler method to compute aerodynamic properties of the wing and solved the dynamic stability eigenvalue problem. These results were compared with and evaluated against, MIL-F-8787c handling qualities limits [10] and flight regulations [11].

Work presented in this paper is a development of the presented concepts. All of the examples from literature that considered dynamic stability constraints are focused only on one type of oscillation: longitudinal or lateral. In reference [7] the whole aircraft has been considered, but authors used simple DATCOM methods

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Nomenclature

ρ	air density	kg/m ³	T_2	time to double	s
C_D	aerodynamic drag coefficient		V_k	particles velocity (displacement) vector in optimization	
C_L	aerodynamic lift coefficient		w	relaxation parameter for particles' global velocity vector from previous iteration in PSO optimization	
C_M	aerodynamic moment coefficient		s_1, s_2	relaxation parameters for particles' components of velocity vector in PSO optimization	
g	gravity acceleration, 9.81	m/s ²	r_1, r_2	random variables in optimization to improve PSO algorithm robustness	
m	mass	kg	F	objective function	
V	flight velocity	m/s	x	optimization design variables	
S	reference area	m ²	μ	optimization constraints parameter	
D	aerodynamic drag	N	q	optimization constraint value	
P	power	W	k	iteration index in the optimization	
σ	stress	Pa			
ε	nodes structure displacement				
ν	safety factor				
ζ	damping ratio				
ω	frequency of oscillations	Hz			

to derive the aerodynamic derivatives that cannot be used for untypical and innovative aircraft configurations. On the other hand, in reference [9] CFD computations have been used to obtain the aerodynamic derivatives but only a single wing was considered.

The boxwing concept was first introduced by Prandtl [12]. The configuration promises benefits in terms of induced drag reduction, decreased mass and higher stiffness [13,14]. These advantages come at a certain price. Joining surfaces of the front and rear wing increase wet area and may introduce additional interference drag. Stiffer, closed loop structure can produce stress concentrations where the wings join [15] and demand precise manufacturing tolerances to avoid problems during structural assembly. Moreover, the configuration has different dynamic stability characteristics than conventional aircraft and like all aircraft, it has to be trimmed and stable. Nevertheless, the boxwing configuration has the potential to outperform classical airplane configurations in certain missions. Researchers today still investigate the potential boxwing designs [16,17] to exploit the advantages of this configuration. Present work was performed during the Polish project MOSUPS (Dynamically Scalable Airplane Demonstrator in Boxwing Configuration) [18,19]. The project was initialized by a preliminary investigation of a boxwing configuration with inverted vertical position of the wings, which caused the positive interference effect of increased lift and reduced drag [20]. The objective of the project was to develop tools and methods for the design of a boxwing aircraft configuration and to build a flying demonstrator as proof of the concept – Fig. 1.

The paper describes multidisciplinary numerical optimization of a whole aircraft, which incorporates automated numerical analysis of aerodynamics, strength, and flight dynamic stability. Many of the simplifications, assumed in the previous research work, were dropped. Numerical computations were made for a complete aircraft. Stability constraints included both longitudinal and lateral stability modes. Additionally, an innovative aircraft boxwing configuration was considered as a demanding task. The presented method of optimization with the flight dynamic stability constraints turned out to be feasible also in this case.

Aerodynamic analyses were conducted with the use of an inviscid 3D panel method and supplemented with a viscous analysis of the wings' airfoils. Geometry of the wings with structural loads was exported to a FEM solver, and the structure was sized by changing the panels' thickness. Having aerodynamic properties and the mass of the aircraft structure from the FEM model, dynamic stability analysis was possible. A full (6 DoF) flight dynamics model [21–24] was used to compute both longitudinal and lateral modes of motion. Constraints on the dynamic properties were imposed



Fig. 1. Boxwing flying demonstrator.

based on the requirements from the MIL-F-8787c handling qualities limits [10].

2. Multidisciplinary optimization framework

The authors have been involved in the creation and development of the computational framework called MADO – Multidisciplinary Aircraft Design and Optimization, which was developed to link existing methods of analysis within an optimization process. Initially only the aerodynamic characteristics of an aircraft were optimized [25]. Later on more sophisticated optimization algorithms were developed [26] and more types of analysis were incorporated during the optimization process [27,28]. Inclusion of the full flight dynamic stability analysis is the latest achievement and is described in this paper.

The general idea of the optimization framework is shown in Fig. 2 according to the convention presented in [29]. Analyses performed during the optimization include aerodynamics, structural analysis and flight dynamic stability analysis. A detailed list of optimization design variables is given in the appendix. There are 24 variables concerning the geometry of the wings and 183 variables which define the thickness of panel sets. The vector of variables x is common to all analyzed disciplines and the disciplines are analyzed sequentially. To maintain the PSO algorithm with a high computational efficiency the particles, which represent different aircraft configurations during a particular iteration, are computed in parallel. Sequence of computations of the particular disciplines is important since results from earlier analyses are used by the subsequent analyses. From the aerodynamic analysis the computational grid of the airplane and aerodynamic loads are transferred to the structural analysis, which is represented by the state variable y_1 in Fig. 2. The grid is modified by adding the primary internal structure of the wings. From the structural analysis, masses of the

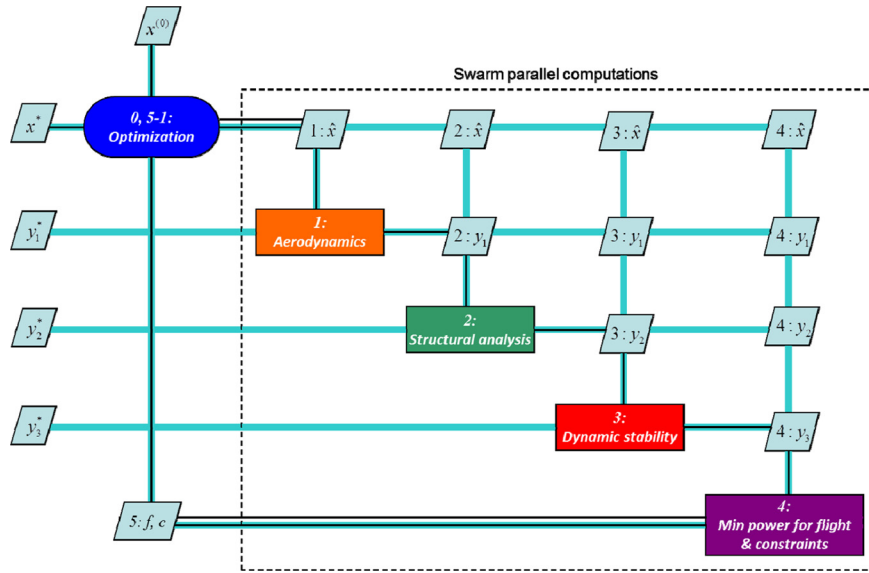


Fig. 2. Scheme of the multidisciplinary optimization framework.

wings are updated as well as the mass of the whole airplane, represented by the state variable y_2 in Fig. 2. The mass properties and aerodynamic derivatives y_3 are needed for dynamic stability analysis and formulation of dynamic stability constraints.

2.1. Aerodynamic analyses

The aerodynamic analyses were done with a low order panel method PANUKL [30], which provides fairly accurate results for 3D aircraft configurations with a satisfactory time for computations giving the non-viscous part of the drag $D_{3D_PANEL_METHOD}$ for the airplane. Since this method does not include viscous analysis, the friction drag of the wings D_{f_WINGS} is calculated using additional analyses of the airfoils of the wings with the Xfoil software [31]. The aspect ratio of the wing was quite significant and the tips of the wings were connected. Infinite wing approximation was used and is well suited for 2D airfoil analyses. The Reynolds number for the airfoils' analyses was corrected due to different chord values and flight velocities for different flight conditions. The viscous drag of the fuselage $D_{f_FUSELAGE}$ was extracted from a separate Fluent [32] analysis and was considered a constant since the fuselage was not changed during the optimization. Additionally, the parasitic drag component $D_{PARASITE}$ was added from the landing gear. The total drag D of the aircraft was computed according to Eq. (1). For every new aircraft configuration new drag computations were done.

$$D = D_{3D_PANEL_METHOD} + D_{f_WINGS} + D_{f_FUSELAGE} + D_{PARASITE} \quad (1)$$

2.2. Structural analysis

Geometry of the wings and aerodynamic loads, in the form of a pressure distribution were exported to the FEM solver CalculiX [33]. The loads were computed for maximum wind gust, which are the critical sizing conditions [14]. The maximum gust occurs for flight speed of 33.5 m/s and gives load factor equal to 4.7. Based on the analysis results, the mass of the aircraft was corrected and additional constraints were imposed defined by maximum allowed stress and maximum node displacement.

Due to the complexity of the optimization framework, the structural analyses make a few simplifying assumptions. Only static analyses of the structure were done and moments of inertia were

based on the estimations for the flying demonstrator and kept constant. Adding more load cases and structural buckling analysis to improve the computational model is considered future work. The simplifications did not change the general idea of the optimization.

The mass of the aircraft was calculated with Eq. (2). Masses of the payload, equipment and fuselage structure were estimated based on the flying demonstrator. The masses of the electric motor and batteries were assumed constant. The mass of the fuselage structure depends mainly on the functionality and concentrated loads, which will not change during the design process. The size of the wing structure and skin thickness is optimized, so the mass of the wing varies. Altered in the optimization, the wings' structure has to withstand stresses during the flight and be stiff enough to deform below the required limits. Both stress and deformation conditions are formulated as the optimization constraints. The maximum allowable nodes displacement in the FEM analyses was limited to 0.1 m.

$$m = m_{fuselage} + m_{wing_struct} \quad (2)$$

2.3. Dynamic stability

The process of computing aerodynamic data for the dynamic stability analysis was fully automated [30]. A number of flight condition cases were computed with the Simulation and Dynamic Stability Analysis (SDSA) software [34], for different flight speeds (28–48 m/s) and altitudes (0–6000 m). Stability analysis involved solving the eigenvalue problem for the full motion matrix [35] and computing the frequency and damping characteristics derived from the eigenvalues of each mode of motion. Obtained results were compared with the MIL-STD [10] acceptability criteria and with CS-23 Airworthiness requirements [11].

3. Optimization algorithm

For the optimization, the Particle Swarm Optimization (PSO) algorithm [36] was used that mimics the behavior of animals gathered in swarms. A swarm consists of selected or randomly drawn particles from a defined search area. A single particle represents an airplane with the current design parameters. The values of the parameters define the position of the particle inside the search area. Every particle tries to find the optimum design parameters through movement in that area. The movement is defined by particle position and the displacement vector V_k . The new position of the

particle is updated with Eq. (4), which utilizes the computed displacement vector – Eq. (3).

$$\vec{V}_k = w \cdot \vec{V}_{k-1} + s_1 \cdot r_1 \cdot (\vec{x}_{best_for_the_particle} - \vec{x}_k) + s_2 \cdot r_2 \cdot (\vec{x}_{globally_best} - \vec{x}_k) \quad (3)$$

$$\vec{x}_{k+1} = \vec{x}_k + \vec{V}_k \quad (4)$$

Constraints are imposed by the quadratic penalty function method. The objective function is increased by the value of the penalty function if the constraint is violated – Eq. (5), otherwise the penalty function is equal to zero. Such a strategy converts the constrained optimization problem into an optimization problem without constraints allowing the solution to use unconstrained optimization methods. The quadratic penalty function is defined by Eqs. (6) and (7). Parameter q defines the boundary value. Effectiveness of the penalty function can be controlled by the μ parameter. Penalty function type constraints can be used with any type of optimization algorithm.

$$F_{Objective-NEW} = F_{Objective} + F_{Penalty} \quad (5)$$

$$\min F_{Objective} \quad \text{for } x > q \quad (6)$$

$$F_{Objective-NEW} = F_{Objective} + \frac{1}{2 \cdot \mu} \sum c^2(x),$$

where $c = \max[q - x, 0]$ (7)

3.1. Optimization algorithm set up

The PSO optimization algorithm used is a part of the author's original code [26]. The optimization algorithm made 25 iterations. In every iteration, 30 individuals from the swarm with different aircraft properties were analyzed in parallel. During the optimization, 209 design variables were allowed to be varied. The global geometry of the aircraft was defined by 24 variables, 183 variables were used to set the panel thickness distributions and the last two were the angle of attack for the whole aircraft and position of the center of gravity. Due to the complexity of the fuselage structure it was assumed that its configuration and mass were fixed. It was also assumed that the desired center of gravity position could be changed by the rearrangement of the avionics and payload positions after the optimization. From experience we could estimate a reasonable range in which the position of the center of gravity, with respect to the fuselage is expected. Position of the wings' attachment to the fuselage and geometry of the wings could change (Table 2 – optimization variables), which would also change the position of the airplane aerodynamic center and the center of gravity.

The optimization algorithm, which had a number of constraints on trim and stability, found optimum values of the design variables. All variables could change within initially defined, reasonable limits. The main objective function was the power needed for level flight – Eq. (8), which depends on the aircraft's mass and aerodynamic properties. To obtain a realistic solution a number of constraints had to be satisfied. During the cruise conditions, weight and lift forces have to be equal – Eq. (9), while the pitching moment coefficient has to be equal to zero Eq. (10). The pitching moment derivative with respect to the lift coefficient, which indicates the level of static stability, had to be lower than the specified value Eq. (11) (smaller value of the derivative – more statically stable aircraft). Local lift force coefficients on the wings could not exceed the maximum lift coefficient Eq. (12). From the structural analysis, constraints on the maximum stress Eq. (13) and maximum displacement Eq. (14) had to be satisfied.

Basic dynamic stability constraints are set by law regulations and more detailed, recommended constraints are described by various additional documents. One of the most complete and known

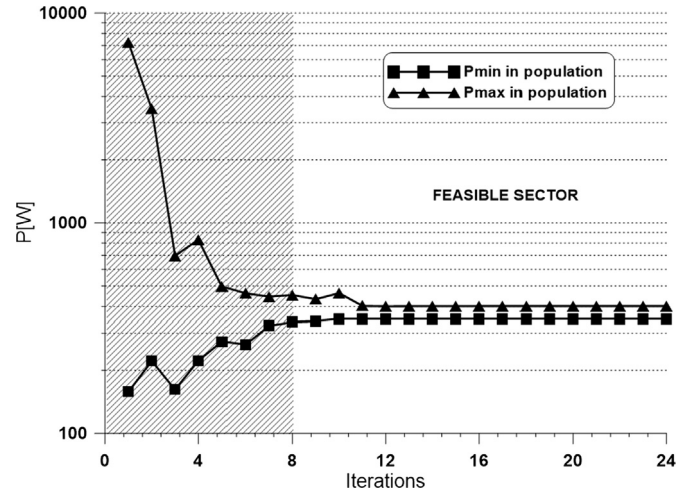


Fig. 3. Objective function convergence history (power for level flight).

are the MIL-STD norms [10], which were applied in the work. Particular constraints for different modes of oscillation used in the optimization are described by Eqs. (15)–(18). These constraints indicate the minimum damping ratio coefficient, the frequencies of oscillation, and the time to double.

Minimize:

$$P_{\min}(X) = \frac{1}{2} \cdot \rho \cdot V^3 \cdot CD \cdot S \quad (8)$$

With respect to:

X (optimization variables vector – see Table 2)

Subject to:

$$m \cdot g = \frac{1}{2} \cdot \rho \cdot V^2 \cdot CL \cdot S \quad (9)$$

$$CM = 0 \quad (10)$$

$$\frac{dCM}{dCL} < -0.15 \quad (11)$$

$$CL < CL_{\max} \quad (12)$$

$$\sigma < \frac{\sigma_{\max}}{\nu} \quad (13)$$

$$\varepsilon < \varepsilon_{\max} \quad (14)$$

$$\zeta_{phugoid} > 0.04 \quad (15)$$

$$0.35 < \zeta_{short_period} < 1.3 \quad (16)$$

$$\zeta_{dutch_roll} > 0.19 \wedge \omega_{dutch_roll} > 1 \left[\frac{1}{s} \right] \quad (17)$$

$$T_{2_spiral} > 20[s] \vee T_{2_spiral} < 0[s] \quad (18)$$

4. Optimization results

Fig. 3 shows the convergence history of the objective function, defined as the power needed for level flight (8). The plot shows results for the worst and the best particle in every iteration. The population gets almost uniform with the optimization solution converging to the optimum. Fig. 5 shows the final geometry of the boxwing aircraft obtained from the optimization. The plot in Fig. 3, appears to show that more power is needed for flight at the final optimum solution, which makes the optimum seem worse than at the beginning of the optimization. However, as it has been noted at the beginning of the optimization all constraints are not satisfied yet (Fig. 4) and the penalty function reduction is the main driver for minimizing the total objective function (7).

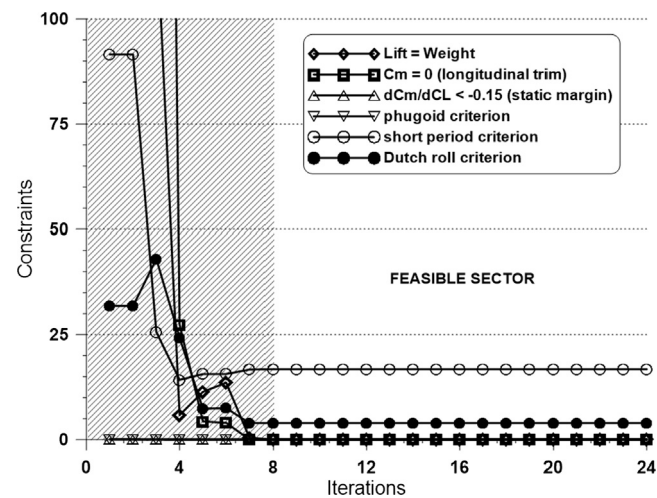


Fig. 4. Constraints convergence history.

Table 1
Main characteristics of the flight demonstrator and its optimized values.

	Demonstrator	Optimized
Wing area [m ²]	0.81	1.97
Wing span [m]	3	4.5
Mass [kg]	24.5	26.1
Cruise speed [m/s]	22	25
Power required for cruise [W]	360	350
L/D	17.5	18.4

Multidisciplinary optimization yields a substantial amount of data. The most interesting results will be presented in following subparagraphs related to different scientific disciplines. The summary of data of the optimized aircraft is presented in Table 1.

4.1. Aerodynamics optimization results

The pressure coefficient distribution is presented in Fig. 6. Thanks to the optimization, the pressure gradients are small and consequently, the pressure distribution on the aircraft's surfaces is very smooth. Fig. 7 shows the lift force distribution on the front and rear wings, which have very favorable distributions. The max-

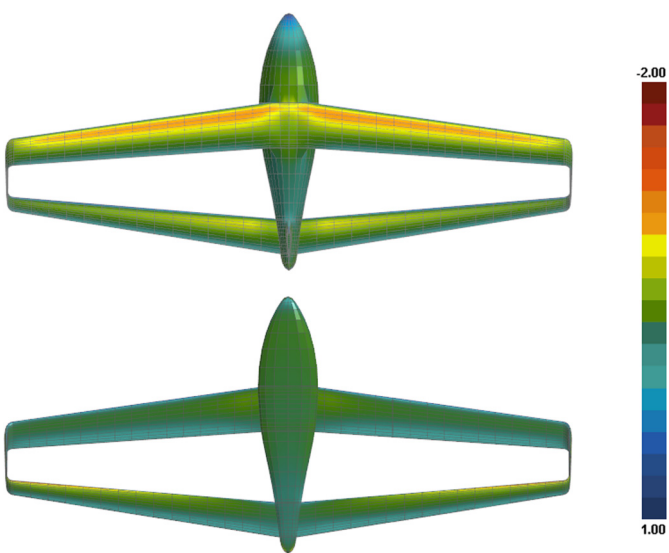


Fig. 6. Pressure coefficient distribution for cruise conditions on the optimized aircraft. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

imum lift coefficient is located in the middle of the half wingspan of the front wing. In the case of the aerodynamic flow separation, the aircraft will still respond to the aileron and flap controls. Most of the lift is produced by the front wing and its aerodynamic center is located close to the center of gravity (about half length of the fuselage). The rear wing acts similarly to the horizontal stabilizer. Placement of the main forces and moments is similar to a conventional aircraft configuration, although it was not restricted by the optimization constraints and could also be similar to, for example, a canard configuration.

4.2. Structural optimization results

Fig. 8 compares von Mises stress distributions in the wing before and after optimization. During the optimization, the geometry of the wings has changed, as well as the panel thickness distribution. After the optimization, stress concentrations, which were present at the wings' roots and at the arcs connecting the main wings with the side wing connectors were reduced. It is also ev-

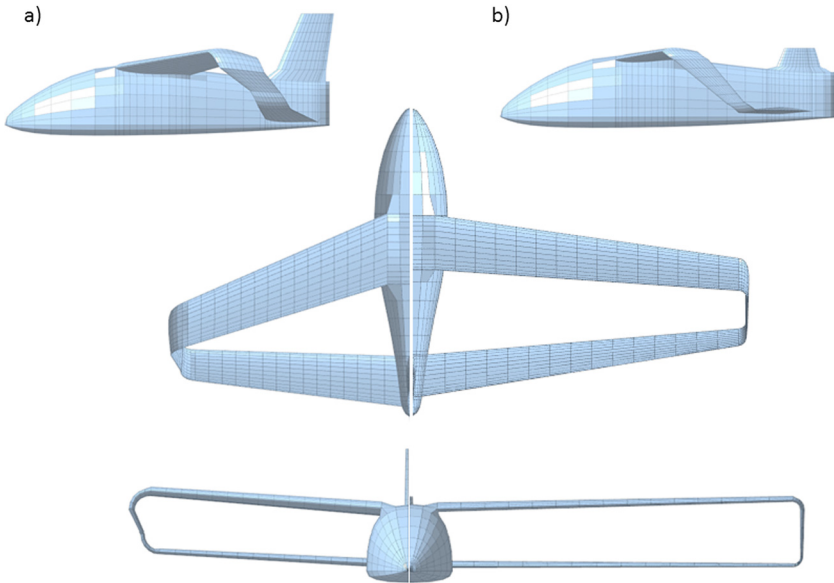


Fig. 5. Geometry of the aircraft (a) base configuration, (b) after the optimization.

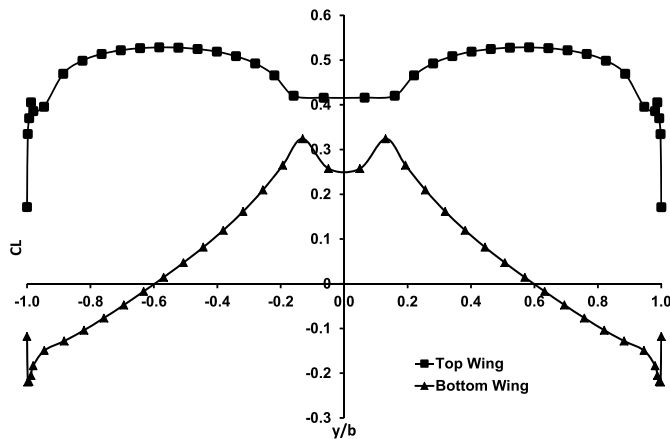


Fig. 7. Lift force distribution on the wings for cruise conditions.

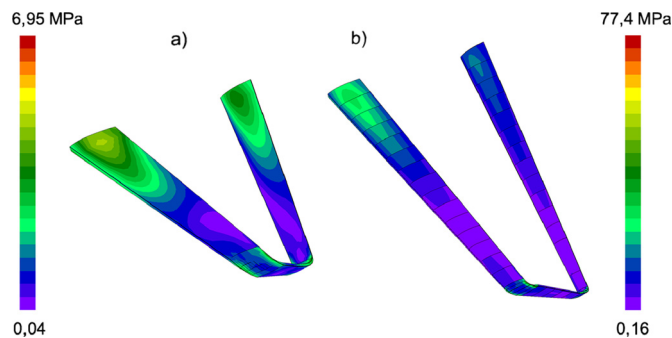


Fig. 8. Mises stress on the wing (a) before optimization, (b) optimized. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

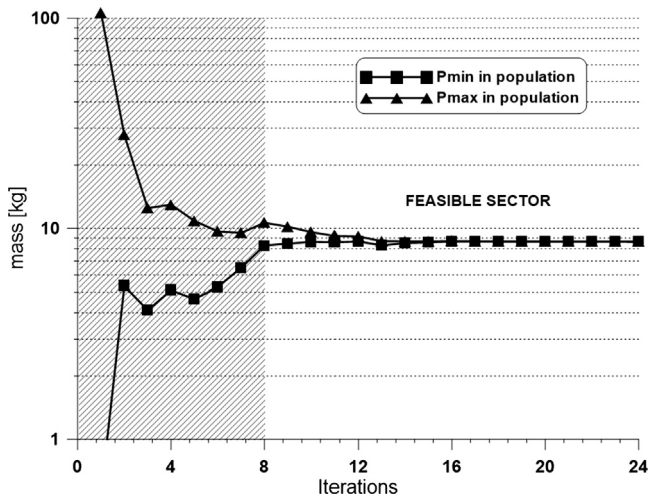


Fig. 9. Mass of the wings convergence history.

ident that the material is better distributed because the stress distribution is more uniform. Fig. 9 shows the process of the mass convergence of the wings, which is the consequence of the structural optimization. The mass of the aircraft was corrected in every iteration since it influenced aerodynamics and flight dynamics characteristics. More details about the structural optimization of the wing can be found in [15].

4.3. Flight dynamic stability optimization results

This part of the article presents results from the dynamic stability analysis obtained within the optimization process. All periodical

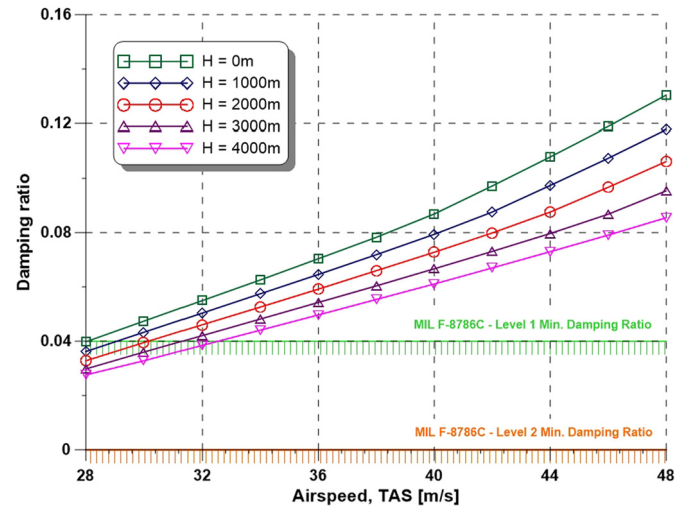


Fig. 10. Phugoid mode – damping ratio.

modes are stable in almost all ranges of tested airspeeds and altitudes of flight. However, there are a few cases where boundaries are marginally crossed. The stability criteria are set as the constraints in the optimization process. The constraints are taken into account using the so-called indirect approach by use of the penalty method. The penalty method does not guarantee that constraints are not crossed, thus in some cases the boundaries can be slightly crossed, which means that the solution is not in the highest level of acceptance, but it is still acceptable.

The optimization process is fully automated after specification of the optimization case and satisfies all the defined conditions. Moreover, the results are obtained for an unconventional type of aircraft with highly coupled aerodynamics, strength and mass properties influencing the dynamics. In contrast to a conventional configuration, common dependencies of the flight dynamics are unknown and it would be hard to satisfy the dynamic constraints with classical methods of design. In the following part, results for particular dynamic modes are discussed.

The airworthiness requirements [11] related to the phugoid are not strong: “Any long-period oscillation of the flight path must not be so unstable as to cause an unacceptable increase in pilot workload or otherwise endanger the airplane” (CS-23.181). Phugoid mode damping ratio is shown in Fig. 10, against the background of MIL [10] criteria. The damping characteristics do not satisfy the Level 1 of acceptance only for slower airspeeds, where it marginally crosses the limits. Fig. 11 shows the time to double phugoid amplitude. Negative values indicate that the oscillations are stable.

The requirements for Short Period oscillations are very strong according to both regulations mentioned above. The CS-23.181 says: “Any short period oscillation not including combined lateral-directional oscillations occurring between the stalling speed and the maximum allowable speed appropriate to the configuration of the aeroplane must be heavily damped...”. The short period undamped natural frequency is shown in Fig. 12. Most of the results are inside the envelope of the second acceptance level according to MIL [10]. In the preliminary stage of aircraft design and for the fully automated optimization process, such results can be considered as very satisfactory. Fig. 13 shows the damping ratio level for the short period mode, which fully satisfies the first acceptance level of the CS-23 requirement to “be heavily damped”.

Results for the Dutch roll mode for flight phase C are presented in Fig. 14. Flight phase C covers the most dangerous phases of the flight – takeoff and landing. It is clear that the constraints are well satisfied. Part of the results have the second level of acceptance for

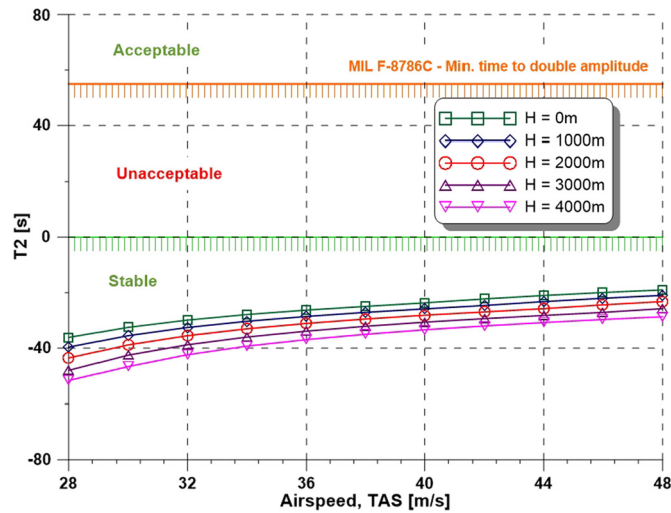


Fig. 11. Phugoid mode time to double amplitude.

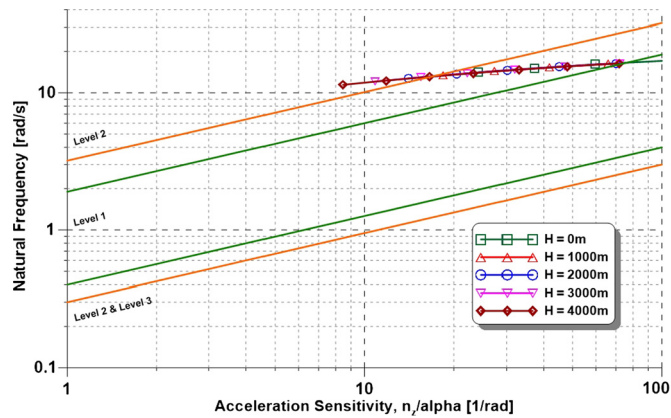


Fig. 12. Short Period CAP (Control Anticipation Parameter) evaluation.

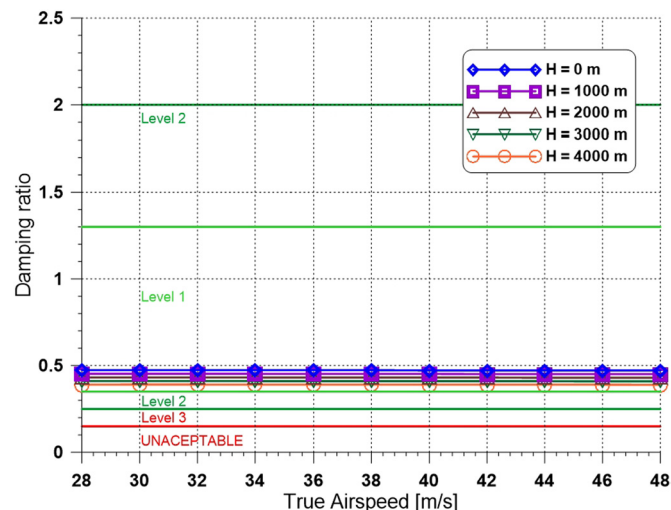


Fig. 13. Short period mode – damping ratio.

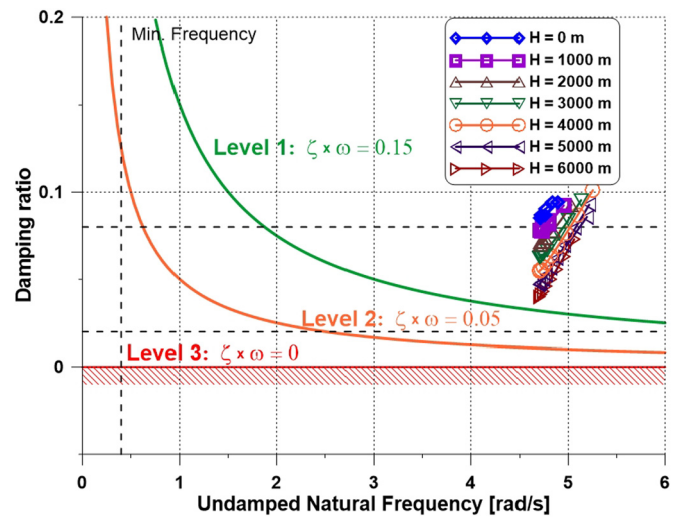


Fig. 14. Dutch roll mode damping ratio from undamped natural frequency for flight phase C.

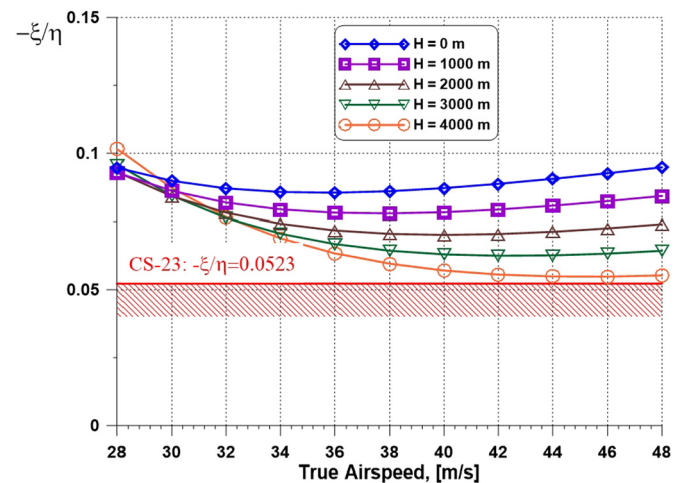


Fig. 15. Dutch roll criteria for CS-23.

tude in 7 cycles...”. The plot in Fig. 15 shows that this requirement is also satisfied.

The roll mode is strongly damped, which is typical for the most of airplanes. The spiral mode characteristics are presented in Fig. 16. Negative values of time to double mean that the spiral mode is also strongly damped, which is very rare because airworthiness requirements are not strong according to CS-23 and MIL-F-8785-C. According to both regulations, spiral mode may even be a little unstable.

5. Conclusion

This work shows how aerodynamics, structural analyses and flight dynamic constraints were coupled in a fully automated numerical optimization process. Computations were shown on an unconventional aircraft configuration, for which all requirements were satisfied. Achieving the goal of optimum design with all constraints satisfied would be very hard, if not impossible with the use of classical methods of design and analysis. The most interesting results of the successful design were presented and discussed.

The first flights of the demonstrator confirmed airworthiness of the boxwing aircraft. However, the pilot reported only basic satisfactory handling qualities of the aircraft. Utilizing the promising

the damping ratio, but for the low altitude in which landing will take place, the acceptance level is one. Dutch roll requirements according to CS-23.181 are given very precisely: “Any combined lateral-directional oscillations (“Dutch roll”) occurring between the stalling speed and the maximum allowable speed appropriate to the configuration of the aeroplane must be damped to 1/10 ampli-

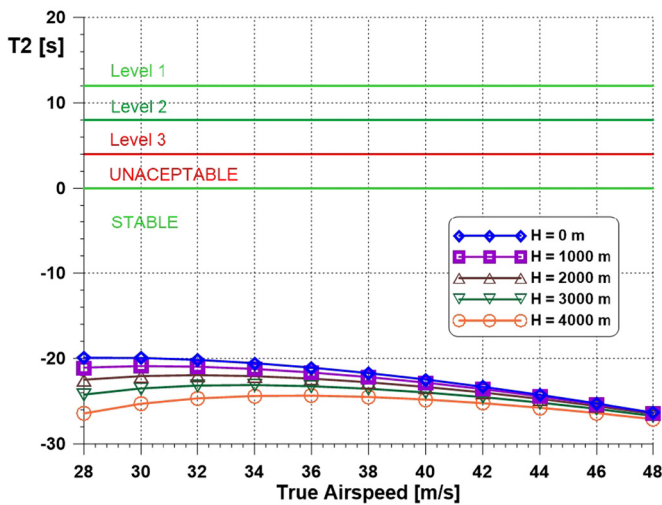


Fig. 16. Spiral mode – time to double.

results from the optimization performed should improve the flight characteristics of the next generation boxwing aircraft.

Application of flight steering constraints or demands is considered as future work in the development of the applied approach.

To the authors' knowledge it was the first attempt to incorporate full flight dynamics constraints in the optimization process of a complete aircraft. The added value of the work is showing the feasibility of the approach to use flight dynamic longitudinal and lateral constraints in the design and optimization process. It was shown that the methodology is even applicable for a complete and unconventional aircraft configuration. The obtained results are close to being used in engineering practice and bring new opportunities in the design process.

Conflict of interest statement

No conflict.

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Appendix A

Table 2 presents all the optimization variables for the presented boxwing configuration. First 24 variables are used to rapid geometry definition according to the idea presented in [37].

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Table 2

Design variables and corresponding limits in SI units (if not stated differently).

Id	Name	Min	Max
<i>High wing</i>			
<i>Root airfoil</i>			
1	Chord	0.2	0.5
2	Alfa [deg]	–2	7
3	x_position	0.65	0.75
<i>Linear part</i>			
4	Alfa	–2	7
5	Sweep [deg]	1	12
6	Dihedral [deg]	0	5
7	Length	1	3.5
<i>Arc</i>			
8	Chord	0.1	0.3
9	Alfa [deg]	–2	7
10	Radius	0.05	0.1
<i>Low wing</i>			
<i>Root airfoil</i>			
11	Chord	0.2	0.35
12	Alfa [deg]	–6	5
13	x_position	1.6	1.6
<i>Linear part</i>			
14	Alfa	–6	5
15	Sweep [deg]	–8	0
16	Dihedral [deg]	–3	3.5
17	Length	1	3.5
<i>Arc</i>			
18	Chord	0.1	0.2
19	Alfa [deg]	–6	5
20	Radius	0.05	0.1
<i>Vertical stabilizer</i>			
21	Chord_root	0.35	0.35
22	Chord_tip	0.15	0.3
23	Sweep [deg]	10	30
24	Length	0.2	0.55
<i>Environmental variables</i>			
25	Alfa [deg]	0	10
26	CGx	0.9	1.15
<i>Structural thicknesses [mm]</i>			
1	th0	0.3	5
...	...	...	...
183	th182	0.3	5

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