UNMANNED AIR VEHICLE 3-D WING AERODYNAMICAL DESIGN AND ALGORITHM STABILITY WITH RESPECT TO INITIAL SHAPE

by

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A new technology of the optimal design of aerodynamic configurations based on a new generation software product is used for aerodynamic design of a 3-D wing of the middle class unmanned aerial vehicle. The optimal shape of the wing, which is characterized by minimum total drag at a fixed lift coefficient and corresponding to the specified geometric and aerodynamic constraints, is determined on the basis of the global search method and numerical solutions of the complete Navier-Stokes equations. It is shown that the proposed approach provides reduction in a wing drag in the cruise flight zone and significantly reduces the material and time costs for aerodynamic aircraft design. Optimal wing has a significantly lower drag at the main design point, and it can be used during cruising and in its vicinity. Optimization allows improving of the glider wing quality. Optimal wing is distinguished by better aerodynamic characteristics in the wide vicinity of design point in terms of the Mach numbers and lift coefficient. Such wing is resistant to the small changes in the flight conditions and it meets all given geometric and aerodynamic constraints.

Key word*: optimal design, full Navier-Stokes equations, non-linear constraints, drag coefficient, pitch moment, algorithm stability*

Introduction

The growing competitiveness in aircraft industry calls for an accurate, efficient, and robust tool for advanced aerodynamic shape design. The main goal of such a tool is to produce a configuration suited to the aircraft mission with the lowest possible flight costs.

In this connection, to additionally underline the importance of drag minimization, consider the task of delivering a payload between distant destinations. The Breguet range equation [1] implies that the operator would have to reduce the payload (and thus reduce the revenue) by 7.6 % to recover the 1.0 % increase in drag. This illustrates that a 1 % delta in total drag is a significant change. In the development of unmanned air vehicle (UAV) aerodynamic design plays a leading role during the preliminary design stage, when the external aerodynamic shape is typically finalized. The final design would be normally carried out only upon the commercially promising completion of the preliminary stage, which makes the preliminary design stage crucial for the overall success of the project.

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In this context, the main goal of this paper is to present an accurate and computationally efficient approach to the multipoint constrained aerodynamic wing design for UAV. In the framework of the method, the total drag of an optimized aircraft configuration is minimized at fixed lift values subject to numerous geometrical and aerodynamical constraints. The optimum search is driven by genetic algorithms (GA) [2] and is based on full Navier-Stokes drag prediction [3], supported by massive multilevel parallelization of the whole computational framework. Over the years, CFD-driven optimization methods appeared [4-12].

The applications include a series of single- and multi-point aerodynamic optimizations for the UAV. It was demonstrated that the proposed method allows us to design feasible aerodynamic shapes that possess a low drag at cruise conditions, satisfy a large number of geometrical and aerodynamic constraints, and offer a good off-design performance in markedly different flight conditions. Presented in this paper approach described in [13-15] for subsonic case.

Statement of the problem and solution method

The input parameters of the aerodynamic configuration design include prescribed cruise lift, Mach, altitude, and minimum allowed drag values, which should ensure the aerodynamic goals of the aircraft mission (such as range, payload, fuel volume, *etc*.). The desired geometry is sought in the class of solutions that satisfy different geometrical, aerodynamic, and multidisciplinary constraints.

The design goal is to develop a geometry with as low a drag at cruise conditions as possible and that, at the same time, satisfies the preceding constraints. The objective of the general multipoint optimization problem is to minimize the weighted combination of drag coefficients at the main design and secondary design points (flight conditions). The solution is sought in the class of wing shapes subject to the following classes of constraints: aerodynamic constraints (such as prescribed constant total lift coefficient and maximum allowed pitching moment) and geometrical constraints on the shape of the wing surface in terms of properties of sectional airfoils at the prescribed wing span locations (relative thickness, relative local thickness at the given chord locations, relative radius of leading edge and trailing-edge angle).

As a gas-dynamic model for calculating C_D, C_L, and C_M values, the full Navier-Stokes equations are used. Numerical solution of the full Navier-Stokes equations was provided by the multiblock industrial code OPTIMENGA_AERO by OPTIMENGA-777 Ltd, which employs structured point-to-point matched grids. The code is based on the essentially non-oscillatory concept with a flux interpolation technique, which allows for accurate estimation of sensitive aerodynamic characteristics such as lift, pressure drag, friction drag, and pitching moment.

For each wing section, the non-dimensional shape of the airfoil (scaled by the corresponding chord) is defined in a local Cartesian co-ordinate system (x, y) in the following way. The co-ordinates of the leading edge and trailing edge of the profile were, respectively, (0, 0) and (1, 0). For an approximation of the upper and lower airfoil surface, Bezier spline representation was used.

As a basic search algorithm, a variant of the floating-point GA [2] is used. The mating pool is formed through the use of tournament selection. This allows for an essential increase in the diversity of the parents. We employ the arithmetical crossover and the non--uniform real-coded mutation. To avoid a premature convergence of GA, we applied the mutation operator in a distance-dependent form. To improve the convergence of the algorithm, we also use the elitism principle.

In their basic form, GA are not capable of handling constraint functions limiting the set of feasible solutions. To resolve this, a new approach has been proposed that can be basically outlined as follows (for more detail, see [13]):

- Instead of the traditional approach in which only feasible points may be included in a path, it is proposed to employ search paths through both feasible and infeasible points.
- With this end in view, the search space is extended by evaluating (in terms of fitness) the points, which do not satisfy the constraints imposed by the optimization problem. A needed extension of an objective function may be implemented by means of GA, due to their basic property; contrary to classical optimization methods, GA are not confined to only smooth extensions.

Results and discussion

Two-point optimization made it possible to reduce the drag coefficient at the optimization point, C_L = 1.20, M = 0.20 at 24.3 aerodynamic counts compared to the base wing (from 400.7 to 376.4). At the point C_L = 1.80, M = 0.20, the value of the drag coefficient decreased by 51.1 counts in comparison with the base wing (from 830.2 to 779.1 counts). Wing shapes according to the results of this optimization in comparison with the shape of the base wing are presented in figs. 1 and 2.

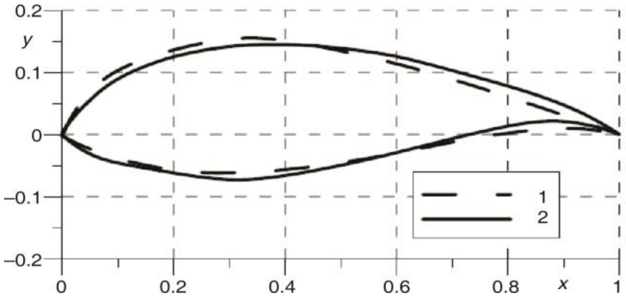

Figure 1. Root section shape for the original (1) and optimal (2) wings

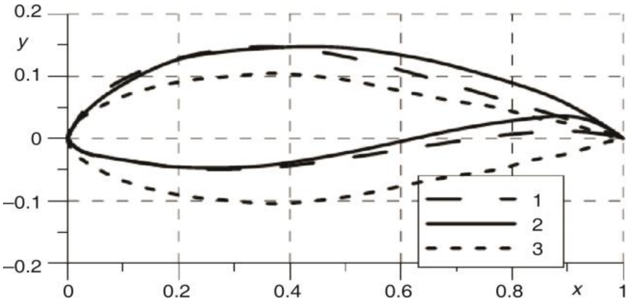

Figure 2. The 2nd crank section shape for the original (1), optimal (2) and *symmetric* (3) wings

Additional information on the local flow characteristics near the optimal wing can be obtained from figs. 3 and 4, which show comparisons of the sectional distributions of the pressure coefficient C_P for the initial and the optimal wing for different cross sections at different points of flight.

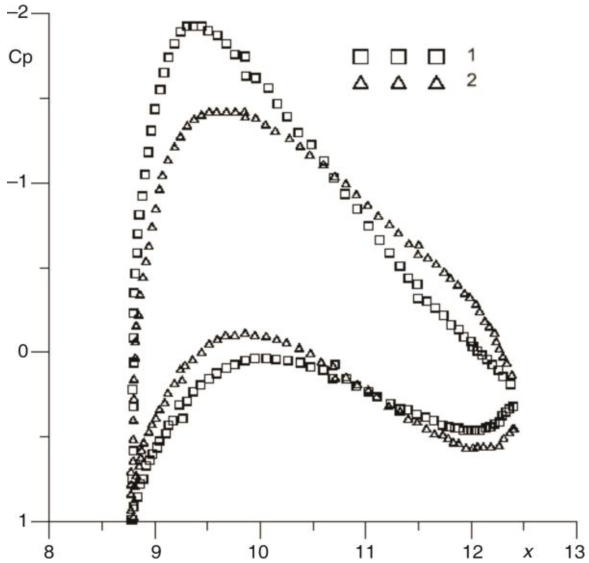

Figure 3. Chordwise pressure distributions in the cross-section Z = 0.0 m over the wingspan at C_L = 1.20 and M = 0.20 for the original (1) and optimal (2) wings

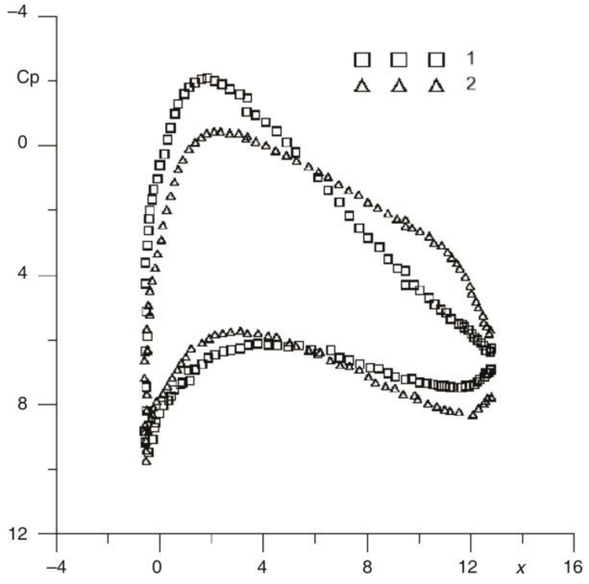

Figure 4. Chordwise pressure distributions in the cross-section Z = 2.15 m over the wingspan at C_L = 1.20 and M = 0.20 for the original (1) and optimal (2) wings

From the analysis of comparisons of the corresponding pressure distributions between the initial and optimal wings, it can be seen that the change in the shape of the wing led to a favorable aerodynamic redistribution of the pressure throughout the entire span of the wing and a significant improvement in the integral aerodynamic characteristics.

This had a favorable effect on the value of the wing drag coefficient at a value of C_L = 1.20, and the resistance decreased for a sufficiently large vicinity of the main design point both in terms of the Mach number and the lift coefficient. This means that the improvements obtained in the design are not local in nature and are resistant to small changes in flight conditions, which is a prerequisite for the practical use of these results.

In conclusion, let us compare the polarity of the resistance between the initial and optimal wings, fig. 5, as well as the corresponding comparisons of the dependence of the lift coefficient on the angle of attack, fig. 6.

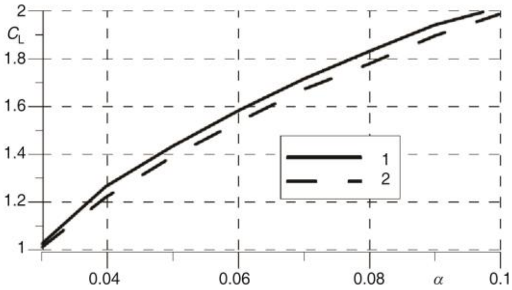

Figure 5. Drag polars for the original (1) and optimal (2) UAV wings at M = 0.20

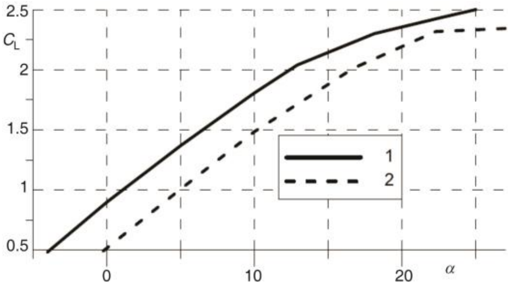

Figure 6. Lift coefficient on the angle of attack for the original (1) and optimal (2) UAV wings at M = 0.20

From a practical point of view, it is very important that the technology yields good results not only when the initial geometry has acceptable aerodynamic characteristics, but also when the initial shape at the design points has a high drag value. As example, we used the initial geometry which was intentionally chosen absolutely unfit from the aerodynamic point of view (symmetrical wing shape, line 3 at fig.2).

Analysis of sectional pressure distributions at the main design point at M = 0.20, C_L = 1.20, as well as pressure at M = 0.20, but with higher C_L value (C_L = 1.50, fig.7) confirmed the assumption that the symmetric profile in the middle of the wing is absolutely unsuitable for these flow conditions. This is also indicated by the value of the drag coefficient at the main design point at M = 0.20, C_L = 1.20, C_D = 445.7 counts - an increase of more than 10% compared to the initial wing.

In the case of *symmetric* initial wing, we have obtained almast the same optimal wing shape as in previous case. Optimal wings have almost the same drag coefficient at the main design point C_L= 1.20, M = 0.20 (C_D = 376.4 counts and C_D = 376.9 counts). Optimal wings have very close (almost identical) integral aerodynamic characteristics in a wide range of flight conditions.

Conclusion

Detailed analysis of the obtained aerodynamic characteristics of the optimal UAV wing shows that two-point optimization has successfully solved the optimal design problem for the wing, since the optimal wing has a significantly lower drag at the main design point, C_L = 1.20, M = 0.20 (C_D = 376.2 counts) and can be operated during cruising at M = 0.20 and its vicinity. Optimization allowed to improve glider wing quality by 7 % and the optimum wing has better aerodynamic characteristics in the wide vicinity of the design point by Mach numbers and the lift coefficient and is stable to small changes in flight conditions. The optimal wing satisfied all given geometric and aerodynamic constraints.

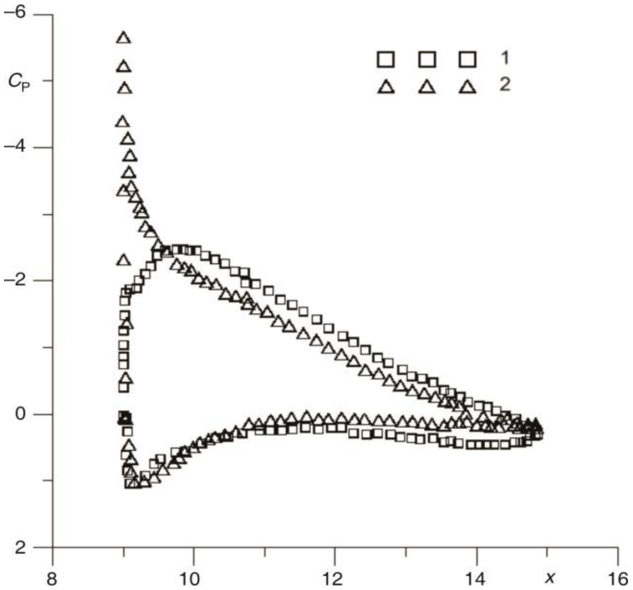

Figure 7. Chordwise pressure distributions in the cross-section Z = 2.15 m over the wingspan at C_L = 1.50 and M = 0.20 for the original (1) and *symmetric* (2) wings

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