Coupled CFD-based Shape Optimization of a Wing of Reusable Space Vehicle of Tourist Class

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Abstract. This article proposes an approach to two-stage shape optimization of the wing of tourist class reusable space vehicle. To achieve appropriate lift and drag force levels, CFD-based optimization methods in combination with geometric parametrisation was applied. During the first stage, the optimization focuses on reduction of wing square and providing required velocity during vehicle’s landing. In this case, for improving the aerodynamic and mass characteristics five geometric design variables were used. The second stage of optimization emphasis on drag force minimization in order to enhance the wing shape in assigned design area by means of adjoint discrete method.

1. Introduction

Nowadays there is an increasing interest in the optimal designing of shapes and lines of aerospace engineering that driven by the need of aerodynamic performance enhancement, reduction of both fuel consumption and carbon dioxide emissions as well as extending range of flight [1]. In this regard, the development of new CFD-based optimization approaches represents the cornerstone for choosing the optimal design path, decreasing number of time- and cost consuming experiments [2-6].

In the present study, the approach to aerodynamic shape optimization of the swept wing of the suborbital reusable space vehicle of tourist class is proposed [7, 8]. Its structure contains V-shaped empennage that consists of two slanted control surfaces that operates as both vertical and horizontal stabilizers and performs the functions of rudder and elevator (Figure 1) [9]. The flight trajectory includes the next phases: lift-off by means of a booster stage, the vehicle’s separation from a booster at altitude of 46 km and the next flight under inertia forces up to maximum altitude of 102 km. At the apogee tourists experience 4 minutes of weightlessness as the vehicle slowly decelerated before its descent into atmosphere and landing. Maximum Mach during entry is 3.6 at an altitude of approximately 40 km.

Figure 1. Three-dimensional geometric model of suborbital reusable space vehicle of tourist class
2. Methodology

As a design case for optimization procedure a time point immediately prior to the landing of the vehicle was assumed in order not to exceed the allowable velocity (not above 250 km/h) and to ensure comfortable conditions of touchdown for crew/passengers. Note, that the vehicle is not provided with a powerplant, therefore it glides into atmosphere under gravity and aerodynamic forces.

Wing shape optimization was conducted in two stages. On the first stage, the optimization problem was stated as follows: minimize wing surface area that involves wing mass reduction. Herewith a constraint on the ratio of lift force in wind axes to vehicle’s apparent weight was used and defined as:

\[
\frac{Y}{m \cdot g} \geq 0.75
\]

where \(Y\) – lift force, N; \(m\) – mass, kg; \(g\) – acceleration of gravity, m/s². This constraint guaranteed the sufficiency level of lift force immediately prior to the landing.

As the vehicle operates in a wide range of velocities, including supersonic, the extra constraint on the minimum wing sweep angle equal to 40 degrees was applied [10]. As design variables geometry dimensions of the wing were considered: \(l\) – length, m; \(\chi = \arctan \frac{b_k - b_0}{l}\) – leading-edge sweep angle, °,

where \(b_0\) and \(b_k\) – root and tip chord, m; taper ratio \(\eta = \frac{b_k}{b_0}\); \(C_{tmax}\) and \(C_{kmax}\) – maximum thickness of root and tip chord, m (Figure 2).

![Figure 2. Design variables of the wing](image)

3. Parametric shape optimization of the wing

To solve optimization problem software environment Ansys Workbench with integrated optimization module was used. For this purpose, CFD analysis in Ansys Fluent in conjugation with geometric parametrization of the wing was applied to determine aerodynamic forces acting on the vehicle whilst landing. Three-dimensional geometric model as the computational domain was created and a set of design variables was defined to represent wing surfaces. The steady-state process of incompressible subsonic flow over the vehicle was simulated. At the inlet of computational domain, the next combination of boundary conditions was assigned: operating static pressure \(P=101325\) Pa, temperature \(T=288.15\) K and flow velocity – 0.18 M [11, 12]. To describe turbulence processes in the flow, two-equation \(k-\epsilon\) turbulence model with standard wall functions was used [13, 14].

Sensitivity analysis of design variables required approximately 100 computations [15]. Herewith design variables were changed continuously in the ranges described in Table 1. Note that to check unicity of obtained design solution, different combinations of the wing geometric dimensions as initial estimates were used.
Table 1. Design variables ranges

| Parameter                      | Value, m | Minimum | Baseline | Maximum |
|-------------------------------|----------|---------|----------|---------|
| Length $l$                    |          | 3,3     | 3,8      | 6,3     |
| Root chord $b_0$              |          | 3,8     | 5        | 5,8     |
| Tip chord $b_k$               |          | 1,5     | 1,9      | 2,3     |
| Maximum thickness of root chord $C_{0\text{max}}$ |          | 0,45    | 0,8      | 1       |
| Maximum thickness of tip chord $C_{k\text{max}}$ |          | 0,07    | 0,15     | 0,22    |

To find the optimal values of the design variables, the gradient-based algorithm named nonlinear programming quadratic line search was used [16]. Based on the sensitivity analysis the most significant design variables were found out and its optimal values were determined. As the result of parametric optimization the geometric dimensions that characterizes root and tip chord were changed in a more critical way compared to the initial wing design (Figure 3) [17]. The wing square was reduced from 11.5 m² to 9.75 m² (15%).

4. Adjoint-based shape optimization of the wing

In the second stage the optimization problem was formulated as follows: minimize drag force with a constraint on lift force with fixed value obtained through previous parametric optimization. The coordinates of finite element nodes were assumed as design variables and could be moved in the defined design area. To solve optimization problem Ansys Fluent with solver Adjoint Solver was applied. The important advantage of the adjoint method is the calculation of the objective function at cost of one flow computation and independence of the number of design variables [18, 19]. The optimization required the evaluation of the objective function derivatives relative to the design variables. Via sensitivity analysis on the baseline geometry the nodes position changes were received, and their maximum was observed at the leading edge. As the result of analysis after 10 computational iterations the new shape of the wing with enhanced aerodynamic performance was obtained (Figure 4). Drag force was reduced by 20% alongside with lift force negligible change within a modelling error of at most 1%.
Figure 4. Shape optimization results and contours of normal optimal displacement (m) for downwind side (a) and upwind side (b) (red filling shows the changes in wing shape)

5. Conclusions
In this study two-stage approach to aerodynamic shape optimization of the wing of reusable space vehicle of tourist class was implemented. Via this approach the optimal wing shape, providing comfortable landing conditions and the required swept angle for appropriate wing operation at supersonic velocities at vehicle’s entry, was defined. By means of geometric parametrization of the wing and subsequent CFD computation, its square was reduced by 15% relative to the baseline for landing case. Moreover, to improve the aerodynamic performance, the optimization by discrete adjoint-based method was carried out. The results demonstrate that the drag force was decreased by 20%.

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