Aerodynamic Optimization of eVTOL Rotor Profiles

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Abstract—Electric Vertical Take-Off and Landing (eVTOL) aircraft are currently being developed to fill a gap in the air transportation sector and, simultaneously, provide zero-emissions alternatives to current generation carbon-intensive short-haul aircraft. However, unlike conventional fixed-wing or rotary aircraft, eVTOL rotors operate in both hover and forward flight configurations. This significantly increases the range of operating conditions experienced by the rotor, introducing multiple aerodynamic design challenges. Additionally, the efficiency of these rotors is particularly important, since it has a direct impact on power draw and aircraft range. In this presentation, a classical airfoil, the ClarkY, is used as a baseline configuration for an eVTOL rotor section. A gradient-based optimization framework using an adjoint solver in Discrete Adjoint with OpenFOAM (DAFoam) with the Reynolds Averaged Navier-Stokes (RANS) approach is then used. In this study, a control point-based free form deformation (FFD) method is used in the framework in order to change the aerodynamic shape. The objective function for this optimization is the lift-to-drag ratio, with additional target lift and geometric constraints. The baseline design is first validated against experimental data, and then the optimization is completed for several target lift coefficient values. Results demonstrate that the lift-to-drag ratio can be increased significantly while maintaining the desired target lift coefficient. Preliminary results for complete rotor optimization using RANS will then be presented, followed by preliminary airfoil optimization using Large Eddy Simulation (LES).

Keywords-component—eVTOL, Optimization, Adjoint method, RANS

I. INTRODUCTION

Urban Air Mobility (UAM) provides economical alternatives to ground transportation and is expected to expand in the future particularly in congested urban areas. Accordingly, electric Vertical Take Off and Landing (eVTOL) for Urban Air Mobility (UAM) is of particular interest. eVTOLs have several advantages compared with conventional aircraft, such as zero emission, low operating costs, and flexible take-off/landing. One challenge for the eVTOL aircraft is the limited energy density of batteries. Thus, improving aerodynamic efficiency is a significant factor in the adoption of eVTOLs. Recently, optimization has been performed using different methods (such as gradient-free and gradient-based methods) in order to increase the efficiency of eVTOL aircraft [1–4].

Qiao et al. [5] presented a rapid contra-rotating propellers (CRP) blade shape optimization framework and studied the impact of the dual propellers revolution speed allocations on overall CRP efficiency. Their investigations were based on the blade element momentum theory (BEMT). They concluded that the optimized CRP is superior to the original by 5.9% in thrust-to-power ratio. The overall efficiency can be additionally increased by 5.3% when the dual propellers share similar torques. There are several studies for distributed electric propulsion (DEP) eVTOL aircraft compared with conventional tilt-rotor configuration [2, 6].

Ma et al. [2] investigated the optimization of the ducted-fan wing (DFW) unit in order to improve both hover and cruise efficiencies. Their conceptual design was based on the vertical meridional plane DFW unit performance analysis. Their results reached 720 km/h maximum speed, a hovering efficiency of 76.3%, and a 10.7 cruise lift-to-drag ratio. Kwon et al. [7] presented a multilevel design optimization framework for an electric motor-driven propeller based on BEMT and computational fluid dynamics (CFD). Droandi [8] implemented the BEMT method and genetic algorithm (GA) to optimize the chord, twist, and section airfoil distribution of a vertical pitch propeller.

Fixed-wing aircraft with vertical takeoff and landing capabilities are believed to offer considerable potential for enhancing aerodynamic efficiency [9]. During the transition from takeoff to cruise, the lift source should move from the rotors to the wing which might complicate aerodynamics. To finish the conversion, the aircraft should have a large stall angle of attack and a high maximum lift coefficient. Chauhan and Martins [10] used gradient-based optimization
studies for the takeoff-to-cruise trajectory of a tandem tilt-wing eVTOL aircraft. Their results were for varying levels of flow augmentation from propellers and found that optimal takeoffs involve stalling the wings or flying near the stall angle of attack. Additionally, they found that without acceleration constraints, the optimized trajectories involve rapidly transitioning to forward flight and accelerating, followed by climbing at a roughly constant speed and then accelerating to the required cruise speed. They also presented the impact of wing loading and available power on the optimized trajectories. Martins [11] reviewed recent developments for aircraft components and presented open-source tools available for aerodynamic shape optimization. A variety of applications including the optimization of a supercritical airfoil, aircraft aerodynamic and aero-structural optimization, and aero-propulsive optimization is presented. Furthermore, RANS-based problems and some of the concerns including comparing Euler and RANS results were discussed Martins [11]. Xia et al. [12] proposed a multi-objective optimization framework for a VTOL propeller using an inverse design method at the cruising stage. Their approach was developed from the Betz optimum theory and BEMT. The maximum thrust-to-weight ratio at hover is considered one of the objectives of their study. They reported the advantages of the variable pitch propeller are both energy saving and takeoff maneuverability.

Recently, there have been few studies regarding small/large-scale optimization problems using different approaches such as gradient-free and gradient-based methods [13,14]. For instance, the Mesh Adaptive Direct Searches (MADS) algorithm can be implemented for derivative-free optimization, which uses a number of variable-size meshes to search the space until convergence is achieved. It has been stated that several investigations have been demonstrated using XFOil and XFLTR solvers in which the potential flow equation is solved for aerodynamic optimization [15]. It has been reported that gradient-based optimization can be an efficient tool for large-scale optimization such as an aircraft’s wing or a whole aircraft by considering a set of design variables in order to maximize the object performance [14,15]. Batay et al. [16] studied the adjoint-based high-fidelity aerodynamic design optimization of a wind turbine by implementing the DAFoam tools. Koyuncuoglu and He [17] simultaneously optimize the wing shape and actuator parameters using high-fidelity computational fluid dynamics with adjoint optimization approach. They stated that their study can be used as the starting point for more detailed high-fidelity coupled wing-propeller aerodynamic optimizations. Negahban et al. [15] used a high-fidelity gradient-based optimization using the discrete adjoint method by the coupling of OpenFOAM and Python within the DAFoam optimization framework. They observed that the number of control points has a significant effect on the optimization process, convergence, and objective function value.

Besides some proposed optimization methods especially regarding trajectory optimization, improving the aerodynamic efficiency of eVTOL components during the take-off and landing stage is quite critical as stated by several researchers. The objective of this work is to implement an adjoint method based on OpenFOAM primal solvers [13] in order to evaluate a ClarkY airfoil that can be used for designing propeller blades in eVTOL aircraft.

II. METHODOLOGY

In this study, DAFoam is used for the optimization which is introduced by He et al. [14]. The DAFoam optimization framework developed in 2019 by the Multidisciplinary Design Optimization (MDO) laboratory team at Michigan University [14] that can handle optimization problems with many design variables coupling with solvers of OpenFOAM. DAFoam is an object-oriented framework to implement discrete adjoint method for any steady-state OpenFOAM primal solvers. DAFoam is a gradient-based optimization in which the adjoint method is used for computing derivatives and considering several numbers of design variables. More details regarding the adjoint method in DAFoam are illustrated as follows.

The objective function consists of both the design and state variables, \( f = f(x, w) \) where \( x \) and \( w \) are the design variable vector and state variables. Additionally, these two variables should satisfy the residual equation, \( R(x, w) = 0 \). The sensitivity of the objective function, \( f \), can be stated as,

\[
\frac{df}{dx} = \frac{\partial f}{\partial x} + \frac{\partial f}{\partial w} \cdot \frac{dw}{dx}
\]

\(
\frac{\partial f}{\partial x} \text{ and } \frac{\partial f}{\partial w}
\)

are cheap to compute while \( \frac{\partial w}{\partial x} \) is expensive as \( w \) is determined implicitly by the residual equation, \( R = 0 \). In order to reduce complexity, the chain rule for residual functions is considered. As \( \frac{\partial w}{\partial x} \) should be zero, the equation \( \frac{dw}{dx} \) is derived as,

\[
\frac{dR}{dx} = \frac{\partial R}{\partial x} + \frac{\partial R}{\partial w} \cdot \frac{dw}{dx} = 0.
\]

Substituting the above equation \( \frac{df}{dx} \) can be rewritten as the following equation.

\[
\frac{df}{dx} = \frac{\partial f}{\partial x} - \frac{\partial f}{\partial w} \cdot \left(\frac{\partial R}{\partial w}\right)^{-1} \cdot \frac{\partial R}{\partial x}.
\]

Then, the transposed adjoint vector is defined as follows and thus the adjoint vector can be obtained.

\[
\Psi^T = \frac{\partial f}{\partial w} \cdot \left(\frac{\partial R}{\partial w}\right)^{-1},
\]

\[
\frac{\partial R^T}{\partial w} \cdot \Psi = \frac{\partial f^T}{\partial w}.
\]

By substituting the adjoint vector equation, the total derivative of \( \frac{df}{dx} \) is,

\[
\frac{df}{dx} = \frac{\partial f}{\partial x} - \Psi^T \cdot \frac{\partial R}{\partial x}.
\]

Thus, the partial derivatives of \( \frac{\partial R^T}{\partial w} \) and \( \frac{\partial f^T}{\partial w} \) are computed and equation 6 yields in \( \Psi \). Then, \( \frac{\partial R}{\partial x} \) and \( \frac{\partial f}{\partial x} \) are calculated.
and finally, \( \frac{df}{dx} \) can be obtained. In order to better understand the algorithm, the details are described by He et al. [14]. The Free-Form deformation (FFD points) displacements are applied to the geometry framework after the optimization process is completed. These points act as control points that are going to be used for changing the mesh. Thus, the framework manipulates the surface mesh by applying the displacements to the FFD points and finally, an updated surface mesh is generated. Here, OpenFOAM’s built-in primal solvers (SimpleFoam) are used. The governing equations are the incompressible NS equations represented by the Reynolds-averaged Navier-Stokes (RANS) equations [12] coupled with the one-equation Spalart-Allmaras (SA) turbulence model.

\[ \nabla \cdot \mathbf{U} = 0, \]  
\[ \nabla \cdot (\mathbf{U} \mathbf{U}) + \nabla p - (\nu + \nu_t) \nabla \cdot (\nabla \mathbf{U} + \nabla \mathbf{U}^T) = 0. \]  

where \( \mathbf{U} \) and \( p \) are the velocity and pressure fields. Here, Reynolds averaged Navier-Stokes (RANS) coupled with the one-equation (the Spalart–Allmaras (SA) turbulence model) is used, although, the KWSST provided us with similar results for this case as well. In the SA turbulence model, a transport equation is solved for a modified turbulent viscosity (\( \nu_t \)), where the eddy viscosity is easy to resolve near a wall. The turbulent eddy viscosity is computed as \( \nu_t = \bar{v} f_{v1} \), where \( f_{v1} = \frac{\chi^3}{(\chi^3 + C_{v1}^3)} \). The one-equation model of the SA turbulent method is given by the following equation.

\[ \nabla \cdot (\bar{v} \mathbf{U}) - \frac{1}{\sigma} \left\{ \nabla \cdot [(\bar{v} + \bar{v}) \nabla \bar{v}] + C_{b2} |\nabla \bar{v}|^2 \right\} - C_{b1} \bar{S} \bar{v} + C_{w1} f_{w} \left( \frac{\bar{v}}{d} \right)^2 = 0, \]  

Constant values of \( C_{b1}, C_{b2}, C_{v1} \) and \( \sigma \) are 0.1355, 0.622, 7.1, and 2/3, respectively. \( d \) represents the distance of a given point in the domain from the closest physical wall. \( \bar{S} \) and \( f_{w} \) are spatial functions associated with the production and the destruction of eddy viscosity, respectively.

### III. PROBLEM SET-UP AND RESULTS

Each section of propellers in eVTOL aircraft consists of an airfoil with different chord and thickness distribution. Here, a ClarkY airfoil with a maximum thickness of 11.7\% at 28\% of the chord and maximum camber of 3.4\% at 42\% of the chord is considered for both the baseline and optimization investigation. The Reynolds number and Mach numbers are \( \text{Re}=200000, \text{Ma}=0.03 \). Thus, an incompressible flow can be considered in this study.

The domain where the airfoil is placed is about 200 times the airfoil chord (as shown in Figure 1). An O-Grid mesh structure with a mean \( y^+ \) of 0.0522 is considered for the current study. As higher \( \text{Re} \) numbers are intended to investigate for further analysis, the small \( y^+ \) is considered for both the validation and the optimization results, although no instabilities have been observed with this \( y^+ \) for the current study. The domain and magnified snapshots of the airfoil and the grid structure are shown in Figures 1 and 2. It should be mentioned that there is no sharp edge in the trailing edge and some bluntness is introduced in the trailing edge of the airfoil. The magnified region of the trailing edge of the airfoil is illustrated in Figure 2.

Regarding the boundary conditions; the velocity for the outer sides of the domain is considered as “inletOutlet” in OpenFoam which indicated that the gradient of velocity on that side is zero unless the flow is inward, where in that case

Figure 1. Computational domain for optimization study

Figure 2. Grid structure for the computational domain for optimization study
it is a fixed value. A fixed pressure B.C is also considered on the outer side of the domain, while the gradient of pressure on the airfoil is assumed zero. The free-form deformation (FFD) method is used in order to parameterize the design surface through the pyGeo package [14]. The FFD points are the blue points around the ClarkY airfoil, as shown in Figure 3, which are 0.01 displaced between the airfoil and points. The first and last sets of FFD points were located at $x/c = -0.01$ and $x/c = 1.01$ (where $c$ is the chord of airfoil), respectively in order to maintain a smooth surface curvature.

First, the baseline design for different angles of attack from 0 to 12 degrees is studied. The lift and drag coefficients for the baseline design can be observed in Figures 4 and 5. The baseline results are evaluated with experimental [18] results and analytical Xfoil prediction which show a good agreement between them. There is a less than 15% error between the current results and experimental results. It should be noted that it is expected that there might be discrepancies between RANS and experimental data, particularly at low $Re$ numbers at low angles of attack since no transition models are being used for the low Reynolds number.

After evaluating the baseline design and obtaining the lift and drag coefficients, the lift coefficients are considered as a target value while minimizing the drag coefficient as the objective function. The process has been performed for all ranges of AOAs. The focus of optimization is on angles of attack prior to the stall situation. Figure 6 shows the finalized airfoil deformation (for some of the AOAs) once the lift reached the target value while the drag coefficient is minimized. It can be seen that by increasing the angle of attack, the deformation in the profile of ClarkY airfoil is highlighted which indicates that the drag coefficient is more reduced at an AOA of 12 compared with zero degrees. Furthermore, the deformation occurred smoothly by increasing the AOAs. This would be an important factor as we require a smooth transition of change in optimizing the whole rotor.

In order to assess the optimization result, the drag coefficient in both the baseline and optimized design is provided in Table I. The last column of this table represents the percentage of optimization in drag coefficient which is defined as $\frac{CD_{\text{optimized}} - CD_{\text{Baseline}}}{CD_{\text{Baseline}}}$. It can be seen that the optimization is more significant at higher AOAs (such as 10° and 12°). Therefore, more deformation can be observed in these AOAs (as also shown in Figure 6). Thus, the adjoint method provides the target lift coefficient while reducing the objective function, which in our case is the drag coefficient.

IV. CONCLUSION AND FUTURE WORK

In this study, a ClarkY airfoil is considered as a section of a propeller blade. As there are limitations in designing eVTOL aircraft such as the storage of batteries in eVTOL aircraft, the aerodynamic performance of components is quite crucial, during take-off, cruise, and landing stages. In the current study, the adjoint method in conjunction with OpenFoam primal solvers (DAFoam) has been used in order to optimize the objective function (drag coefficient). By finding the lift target coefficient for each AOAs using baseline design, the drag coefficient is optimized. It has been observed that the optimization is more than 5% in AOAs > 6° and the drag coefficient can be reduced as 18% which would be significant for a rotor design. The optimization method can be implemented further in the whole chord distribution of a propeller blade in order to find an optimized propeller in eVTOL regarding the design variables and objective function.
in future work. Furthermore, the objective function can be changed to investigate acoustic optimization as well. Results from unsteady gradient-free optimization will be presented at the conference.

![Optimized ClarkY airfoil for different AOA](image)

**Figure. 6.** Optimized ClarkY airfoil for different AOAs

<table>
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<th>AOA</th>
<th>C\textsubscript{L}-target</th>
<th>C\textsubscript{L}-Baseline</th>
<th>C\textsubscript{L}-Optimized</th>
<th>Optimization %</th>
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</tr>
</tbody>
</table>

**TABLE. I**

Comparing Aerodynamic Efficiency of the Optimized Airfoil for Different Target Lift Coefficient

**REFERENCES**


