Wing conceptual design for the airplane with distributed electric propulsion

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Abstract. This paper is focused on the usage of distributed electric propulsion (DEP) in order to increase aerodynamic efficiency. A ten seats aircraft is used as a case study. New design uses the existing fuselage, tail and turboprop engine, only wing is completely redesigned. The cost function for the design procedure consists of two parts. The first one is aerodynamic efficiency, which has a primary impact on fuel consumption, and the second one is weight of the wing. Lifting line theory with blade element momentum theory is used to design a wing geometry with DEP. Optimal geometry is also verified by CFD simulation. The estimation of the wing weight is needed for the second part of the cost function. This was done by the design of elementary wing parts under CS-23 regulation. The wing is assumed as full-aluminium with two spars. The main goal of this optimization is to redesign the wing for a given range and save as much fuel as possible.

1. Introduction
Distributed electric propulsion (DEP) is a promising concept for future aircraft development [1]. This concept uses many electric motors with propellers installed at the wing leading edge. The flow accelerated by the propellers causes increase of the lift and thus smaller wing area is necessary for given landing velocity. This leads to lower drag in cruise regime and lower fuel consumption which corresponds to the latest challenges connected with minimizing environmental impact of air transport.

DEP itself brings many new design problems. Some examples from the literature represent e.g. design of airfoil suitable for both landing and cruise [2], installation of DEP on traditional aircraft [3] or hybrid-electric systems [3]. The present paper represents continuation of the work presented by the authors in [4]. The approach is based on the modification of the single-engine CS-23 category aircraft. The aim is to modify the wing in order to improve fuel consumption for given standard flight. The wing is modified by reduction of wing chord, i.e. lower wing area and lower drag in cruise regime, and by DEP installation on the leading edge. Multidisciplinary optimization is performed in order to determine optimal way of wing modification. DEP is used only for take-off and landing. Original propulsion system represented by the turboprop engine and constant-speed propeller is used for cruise conditions. Performance of original and modified aircraft is compared.

2. Redesign of the wing
In this part a geometrical shape of the wing is selected for the cruise regime. After that a fuel saving is estimated, and for this mass a distributed electric propulsion system is designed. In the next step the wing structural analyses are performed for weight estimation of the designed and original wing.
2.1. Wing area selection and fuel saving

In the previous work [8], several wings with different wing areas with constant wing span were calculated. As baseline geometry an Ae270 aircraft is choose in this work. It is a 10 seats aircraft designed by Aero Vodochody Company. Our mission is defined by maximum take-off weight 2500 kg, cruise speed 400 kph at 20000 feet altitude. For the comparison of aerodynamic characteristics, a nonlinear lifting line was used [5]. Due to these calculations a half area wing, related to the original wing, is selected as a solution with significant drag reduction in cruise regime and acceptable small wing area. Wing aerodynamic drag reduction of the wing is around 30%.

The aerodynamic characteristic of the original wing is compared to the wind tunnel result of the whole airplane (fig. 3). It could be seen a relatively good correlation for lift coefficient from 0 to 1, cruise regime has a lift coefficient around 0.3. After that, a drag of fuselage and tail is estimated as \( c_{D0} = 0.011 \). Total aerodynamic drag for both selected wings are then calculated by this formula:

\[
c_D = c_{D_{wing}} + c_{D0}.
\]

Nacelles for electric engine and folded flap is not considered in this simplification. This kind of approach is used for preliminary design purposes and will be investigated by CFD calculation in the next work.

Total fuel consumption is calculated in an iterative program developed in Matlab. The total aerodynamic drag is interpolated for required lift in each computational loop. Actual fuel consumption is then calculated. Specific fuel consumption 0.366 kg/kWh is considered of PT6A-42 jet engine and the iterative process is repeated until reaching a 2500 km range. Both wing geometries are simulated in the same way and the result shows the aircraft with original wing consume 690 kg of fuel and the aircraft with half-area wing consume 428 kg. After that, we decided to use a part of saving weight to design a distributed electric propulsion system.

![Figure 1. Geometry of wings with different area](image1)

![Figure 2. Aerodynamic characteristics of wings with different area, calculated by lifting line theory. Colours for different wing configurations correspond to fig. 1.](image2)

![Figure 3. Comparison of aerodynamic polar for wind tunnel result of the whole plane, wing calculation and correction of calculated wing to total aerodynamic drag](image3)
2.2. DEP sizing and propeller design

Each element of DEP has itself a ratio value to the weight. There are defined engine power to weight ratio $\dot{m}_e = 5.8$ kW/kg [6], electronic speed controller power weight ratio $\dot{m}_{ESC} = 30$ kW/kg, battery $\dot{m}_B = 165$ Wh/kg and wires $\dot{m}_C = 2000$ A/(kg.m). Then an equation that calculates available power is defined. Mass on the left side has been chosen $m_0 = 144$ kg, $d$ is length of wires, $U$ is voltage and $t = 120$ s is desired time pro DEP system:

$$m_0 = \frac{p}{\dot{m}_e} + \frac{p}{\dot{m}_{ESC}} + \frac{p}{\dot{m}_B} + \frac{p}{\dot{m}_C} \cdot \frac{d}{U}$$  \hspace{1cm} (1)

This enables the usage of more than 338 kW power for DEP engines. An analytical approach was developed for determination of the number of engines and its propeller size. Crucial rule to design of DEP system play landing requirement, especially minimum air speed. The relation between original wing and selected half-area wing is described in the following equation:

$$\frac{1}{2} \rho v_0^2 c_L S_{ref} = \frac{1}{2} \rho (v_0 + v_i) c_L \frac{S_{ref}}{2}$$  \hspace{1cm} (2)

where $S_{ref}$ is area of original wing, $\rho$ is air density, $v_0$ is freestream velocity and $v_i$ is propeller induced velocity. From this we can determine the value of the required induced speed. Then actuator disk theory and geometrical relation is used and after rearrangement and simplification we get final relation that calculates number of engines [8]:

$$n = \frac{\eta_{prop} \rho i^2}{P_{tot}} 2 v_0^3 (\sqrt{2} - 1)$$  \hspace{1cm} (3)

where $\eta_{prop}$ is efficiency of propeller, $i$ is semi-span wing and $P_{tot}$ is amount of power from eq (1). The shape of the propeller is designed by theory of Minimum Induced Loss [7]. Input variables for this kind of procedure are number of blades, RPM, propeller diameter, airspeed, power and airfoil aerodynamic characteristics. Thus we get twist and chord distribution across the blade. The geometry of the propeller is used in the CFD calculation in the next step.

2.3. Wing stress analysis

The main structural parts of the wing are designed to estimate the weight of the wing. Aerodynamic forces and moments acting on the wing are used to calculate shear force, bending moment, and torque moment. Limit Manoeuvring Load Factors is considered for commuter category aeroplanes in this work (vertical limit load factor $n = 2.8$). Moreover, a factor of safety is used. It means the aerodynamic loads are for the purpose of structural design multiplied by 1.5. All-metal wing is considered in this work and typical aerospace aluminium alloy AW-2024 is used. Aerodynamic loads and pitching moment distribution are calculated using nLLT [5]. In the first step of the design procedure, the distribution of the ribs is chosen. In the second step, a flange, that transmits the bending moment, is dimensioned. Column buckling is considered and empirical characteristics to determine critical stress are used. And finally, the thickness of the web and skin is calculated. A double-spar wing section with two cells is used in this case, and shear flow analysis is solved. We are also using empirical characteristics to determine critical stress for flat thin panel and curved plate. In the following picture, a schema of ribs distribution and two spars are depicted.

![Schema of ribs and spars distribution](image)
The result mass distribution for both wing geometries is shown in the fig. 4. Both pie graphs are for one half of the wing. On the left side can be seen mass distribution for the original wing. Most of the weight of the wing is caused by the panel skin. On the other hand, the half-area wing has lower weight and the heaviest part is flanges. It is caused by lower effective height of the spar and higher tension and compression acting on flanges.

### Figure 5. Comparison of structural weight of the wing (half part of wing)

### 3. CFD analysis of wing

An influence of DEP is validated by numerical simulations within OpenFOAM solver. First, aerodynamic characteristic of flapped wing segment without DEP is simulated and then a propeller is added in front of the leading edge. DEP is applied at the wing segment with flaps in landing configuration. Numerical method is validated on airfoil with 30% flap deflected to 30 ° by comparison with characteristics obtained from wind tunnel experiment [9]. Mentioned wing segment is 600 mm width with 785 mm chord. Flap with 30% depth is deflected to 30° in position with maximum lift coefficient which was obtained from wind tunnel testing. Mentioned wing segment has a rectangular shape. Three bladed propeller has a diameter of 580 mm, which geometry with respect to the minimum induced drag in the design regime, according to Larabee's method. The propeller is powered by a 16kW electrical engine located in nacelle. Propeller plane is perpendicular to flight direction in cruise regime and is located 300 mm in front of the leading edge. The propeller is considered as tiltable into the engine nacelle. The presence of nacelle is neglected in CFD simulations. Nacelles were considered in previous simulations with DEP on the whole airplane and they will be considered in future simulations as well.

Computational mesh around wing segment in cruise regime is realised as 2.5D trimmed mesh, meanwhile flapped wing is realised 3D trimmed mesh. Computational mesh for DEP simulation is refined in the propeller region. Simulation is in all cases done with the k-ω SST turbulence model as
incompressible. Turbulent model has been chosen to catch drag characteristic more accurately, while low \( Y^+ \) close to one are applied on wall boundary conditions. Negative side of used turbulent model is production of some large turbulence levels in regions with large normal strain, like stagnation regions and regions with strong acceleration. These regions are at this application only at very limited locations, so used model can be used for normal regimes. At higher angle of attack, in combination with type of mesh, the drag prediction can be poor. In order to increase simulation stability, the velocity limiter set to 270 m/s was applied.

**Figure 7.** Comparison of wind tunnel and calculated lift for airfoil with 30% flap deflected

**Figure 8.** Curve of lift coefficient as a function of angle of attack for both flap and blown flap configuration

From CFD simulations, the increase of the lift coefficient almost by twice is visible. Future simulations will be focused on whole aircraft with nacelles in cruise regime, and flapped wing segment with nacelles. Influence of DEP is depicted on the following chart and figures with streamlines and pressure fields in the middle of the wing section.

**Figure 9.** Streamlines on flapped wing without (left) and with (right) DEP
4. Conclusion
The usage of a distributed electric propulsion (DEP) is investigated in this paper in order to increase aerodynamic efficiency. Generic ten seats aircraft is used as a case study. The new design uses the existing fuselage, tail and turboprop engine, so only the wing is modified. The cost function for the design procedure consists of two parts. The first one is aerodynamic efficiency, which has a primary impact on fuel consumption. The second one is the weight of the wing.

Various methods are used for design analysis. Lifting line theory with blade element momentum theory is used to design a wing geometry with DEP. A simplified model without nacelles is considered in this conceptual approach. Optimal geometry is verified by CFD simulation. Wing weight is determined so that the new design complies the requirements of the CS-23 regulation. The wing is assumed as full-aluminum with two spars.

The selected optimal configuration has 50% area in comparison with original configuration. The analysis shows that this can reduce fuel consumption by 38 % in cruise. Usage of DEP leads to the same landing and take-off velocity as original design. Wing structural design shows possible significant weight reduction for the smaller wing and moreover is potential for further weight reduction due to usage of thrust braced wing. This is a possible theme for future work.

5. References
[1] Kim, H. D., Perry, A. T., and Ansell, P. J. (2018). A Review of Distributed Electric Propulsion Concepts for Air Vehicle Technology. 2018 AIAA/IEEE Electric Aircraft Technologies Symposium. doi:10.2514/6.2018-4998
[2] Sze S M 1969 Physics of Semiconductor Devices (New York: Wiley–Interscience)
[3] Viken, J. K., Viken, S., Deere, K. A., and Carter, M. (2017). Design of the Cruise and Flap Airfoil for the X-57 Maxwell Distributed Electric Propulsion Aircraft. 35th AIAA Applied Aerodynamics Conference. doi:10.2514/6.2017-3922
[4] Moore, K. R., and Ning, A., “Distributed Electric Propulsion Effects on Traditional Aircraft Through Multidisciplinary Optimization,” AIAA Structures, Structural Dynamics, and Materials Conference, Kissimmee, FL, Jan. 2018. doi:10.2514/6.2018-1652
[5] Hospodar, P., Klesa, J., and Zizkovsky, N. (2018). Wing and propeller aerodynamic interaction through nonlinear lifting line theory and blade element momentum theory. MATEC Web of Conferences, 233, 00027. doi:10.1051/matecconf/20182330027
[6] EMRAX electrical engine, 2018, https://emrax.com/products/emrax-208/
[7] Larrabee, E. E., Practical Design of Minimum Induced Loss Propellers, Business Aircraft Meeting and Exposition, Society of Automotive Engineers, Warrendale, PA, April 1979, Paper 790595
[8] Hospodar, P., Klesa, J., and Zizkovsky, N. (2019). Design of distributed propulsion system for general aviation airplane. MATEC Web of Conferences, 03009. doi:10.1051/matecconf/201930403009
[9] McGhee,Robert J. ; and Beasley, William D. : “Low-speed aerodynamic characteristics of a 13 percent thick medium speed airfoil designed for general aviation applications”. NASA-TN 1498,1979.

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