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Reducing Fuel Consumption by Aerofoil Optimization

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Abstract

This work deals with aerofoil aerodynamic features optimization, not only to improve flight features, but also to improve economy, ecology and safety of parameters of flight technique. In cruise mission, occupying the most flight time, the most important parameter is aerodynamic drag, which directly in-fluences the aircraft operational economy of transportation. Drag reduction is adequately reflected in the fuel consumption re-duction. Consumption reduction is also adequately reflected in the flight ecology. In take-off and landing mission, the safety is priority and directly influences the aerofoil geometry. For cruise mission the new modified evolutionary algorithms (EA) are used to input parameters to Bezier-PARSEC 3434 parameterization. Such aerofoil is processed and evaluated by the Xfoil program. The change of model parameters results to optimal aerofoil shape.

The Direct Control Aerofoil Geometry (DCAG) is unique developed device, which provides changing of curvature of aerofoil, and also aerofoil geometry. DCAG is based on the rotary principle, which makes possible to define the curvature of aerofoil for every roll as well as defining the geometry in the variable parts of aerofoil. For take-off and landing mission the best combination of slots and flaps is chosen. DCAG is used to improve of laminarity and reduce turbulent flow. The work results to optimization, which is more times faster in comparison to ordinary optimization, with minimum of input parameters (flight speed, chord length, range of angles of attack and fitness function). The optimized aerofoil can achieve significant fuel savings compared to the non-optimized wing aerofoil. The output was checked by ANSYS Fluent simulation.

Keywords: Evolutionary algorithms; Shape of aerofoil; Optimization of shape; Bezier-PARSEC model

Introduction

Optimal design of aircraft technology is a multidisciplinary problem. Aerodynamics, design, acoustics, manufacturing and economics are some of the disciplines involved in this type of problem. Solutions of only one of these disciplines may lead to conflicting requirements (e.g. optimization of lift and drag against strength and weight requirements). EA methods are based on the population, simulating the development of species and survival of the strongest and compared with traditional optimization techniques have advantages. In practice the first advantage is faster convergence to optimal solutions, in addition, they can manage differentiated fitness functions. Second advantage is simplicity, when the EA uses only function values for each candidate design. They do not require substantial modifications or complex interfaces for use. EA provide completely new design solution and reduction of aerodynamic drag. As a result, fuel consumption is reduced as a result of reduced airplane power requirements.

In our case, for solving of aerofoil aerodynamics was used numerical optimization of EA, with results checked by Computational Fluid Dynamics (CFD). This optimization of aerodynamic aerofoil features is followed by Direct Control Aerofoil Geometry (DCAG) according to patent [1]. DCAG provides improving of aerodynamic lift to values unreachable by present technologies. As a result, this means a radical reduction in the need of take-off and landing runway length. Reducing the landing speed results in higher airplane safety. Next result is increasing of the maneuverability of the airplane using possible several of aerofoil shapes along the whole span of wing. DCAG is also useable for other types of transport such as boats, ships, submarines, etc. Every flight mission has different requirements to [2] aircraft aerodynamics. The ability to change the aerofoil geometry (morphing) during flight increases safety and reduces fuel consumption, which are the main aircraft requirements. Such morphing is reflected to flight and operational features improvements. Nowadays the flaps and slots are used to change aerofoil shapes for take-off and landing flight missions. Generally, the morphing allows aerodynamic lift increase to a level that provides the safer aircraft take-off and landing at the lowest possible aircraft speed and shortest possible runway.

The actual flight, i.e. the aircraft relocation from one geographical point to another, is already a compromise be-tween the highest aerodynamic lift and the lowest aerodynamic drag to make the flight as economical as possible. This type of aircraft relocation is mainly used for civil area, for which the economic aspect is most important. The developed design solution is so universal that it can be used not only in aviation technology, but also in other areas, such as wind turbine blades, unmanned aerial vehicles, but also the F1 cars spoilers or water turbine blades.

Present State

Nowadays various mechanisms are used to improve the aerodynamic features. But such mechanisms split the aerofoil into more segments, which results to discontinuation of laminar flow. Various attempts have already been made to develop aerofoil as one segment, but only mechanically complicated solutions were developed (Figures 1 & 2).

Figure 1: Turbulent flow.

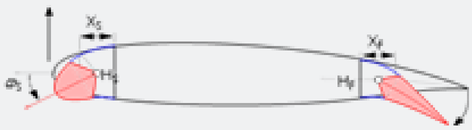

Figure 2: Laminar flow.

In general, there is an effort to develop an aircraft with one segment aerofoil for all flight missions and with slots and flaps used. One segment aerofoil supports laminar flow, which positively influences aerofoil aerodynamic features. It reflects to economy, ecology and flight safety improvement. An example is the AFTI / F-111 fighter (Figure 3).

Figure 3: Fighter AFTI/F-111.

Project AFTI/F-111

By the end of the 1960s, the first tests were made when NASA worked to evaluate the problems of the first F-111A for the Air Force and Navy [3]. In the 1980s, the supercritical wing was replaced by the Boeing MAW wing. The concept is based on US Patent No. US 4,335,502 (1982), (Figure 4). The result was increase of range by 25%, improvement of lift/drag ratio by 20%. Despite these good results, the fighter was not produced, because of constructional complexity.

In addition to the one segment aerofoil, the aerofoil shape is also reflected in the aerofoil aerodynamic features. The optimization is used to find aerofoil with best aerodynamic features. Such optimization helps to find the optimal solution, therefore optimal aerofoil shape. An example is the ATR-42-4 airplane.

Project ATR-42-4

An example of aerofoil shape change is ATR-42-4 [4-7], when the aerofoil shape modification is realized by the morphing of the upper side of the aerofoil, as shown in Figures 5 & 6.

The genetic algorithms are used for aerofoil shape optimization. Every individual in population is defined by two real values, representing the stroke of the actuators. This stroke values are between original aerofoil and morphed aerofoil. The fitness function was defined to calculate individuals in population and to reach aerofoil drag minimization. Approximation of the upper deformed part is realized by cubic spline. The aerofoil features are represented by the Reynolds number and the angles of attack, which are converted into a batch file. The aerofoil coordinates (x, y values) must be available for the Xfoil program, which calculates

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the aerofoil lift and drag values. Drag decreasing of up to 26.73% was reached by such aerofoil geometry optimization. Also drag decreasing results to a reduction in fuel consumption of more than 20%. The lift also increased significantly, especially in the range of small, positive and negative lead angles.

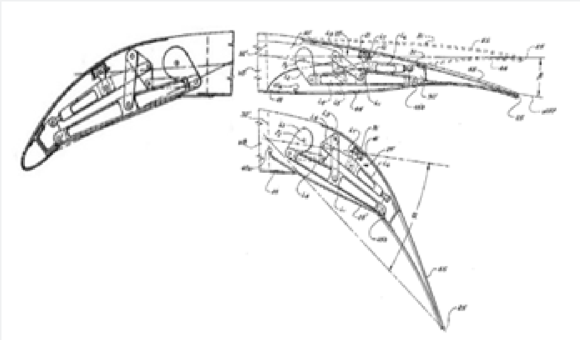

Figure 4: Patent US 4351502/1982.

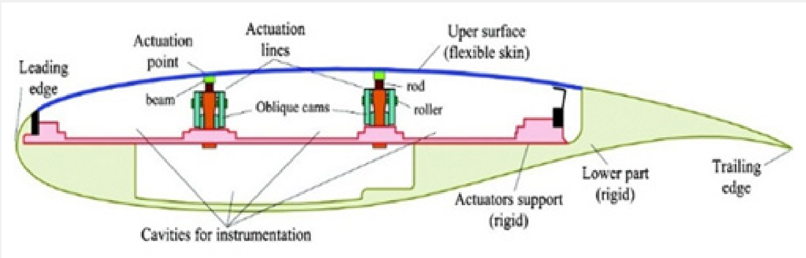

Figure 5: Aerofoil morphing mechanism ATR-42-4.

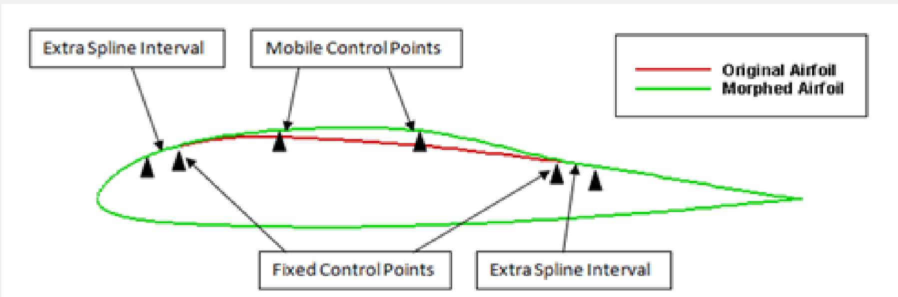

Figure 6: Aerofoil morphing results ATR-42-4.

Parameterization for Cruise Mission

The aerofoil aerodynamic shapes are represented by individual coordinates. But in the case of optimizing and working with many aerofoils, it is necessary to represent the aerofoil shapes by several parameters. The aerofoils representation using only a few parameters is called parameterization. The advantage of parameterization is aerofoil characterization by several parameters in comparison with coordinates counting most often several hundred values.

Bezier-PARSEC 3434 Parametrization Optimization

This method is combination of parametrization Bezier and PARSEC techniques. By such combination the Bezier-PARSEC method gains advantages provided by both mentioned parametrization techniques [8-10]. The Bezier-PARSEC 3434 parameters are used for optimization application. The model needs 6 parameters for aerofoil thickness and 8 parameters for aerofoil camber. The BP3434 parameters crossover, mute and randomly change. The thickness and camber from Bezier-PARSEC make the shape of aerofoil, which is normalized to x, y coordinates (Figures 7 & 8).

New Modified Evolution Algorithms for Cruise Mission (EA)

The difference in aerofoil aerodynamic features optimization is in obtaining of aerofoil. While cruise mission gains aerofoil

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from Bezier-PARSEC 3434 parametrization optimization, the landing obtains aerofoil from a combination of depth, slot angles and depth, flap angles. For take-off no optimization is used [11] (Figure 9).

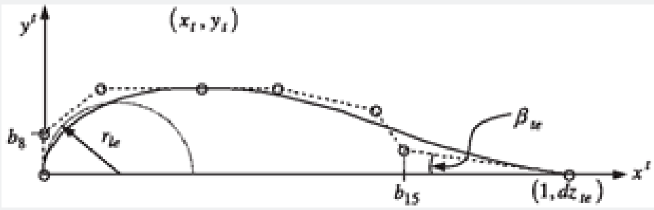

Figure 7: Bezier-PARSEC 3434 thickness.

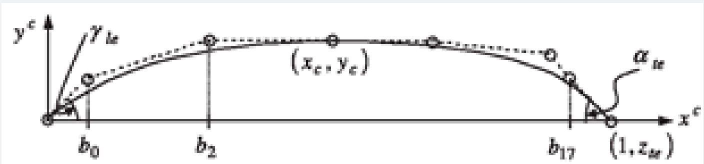

Figure 8: Bezier-PARSEC 3434 camber.

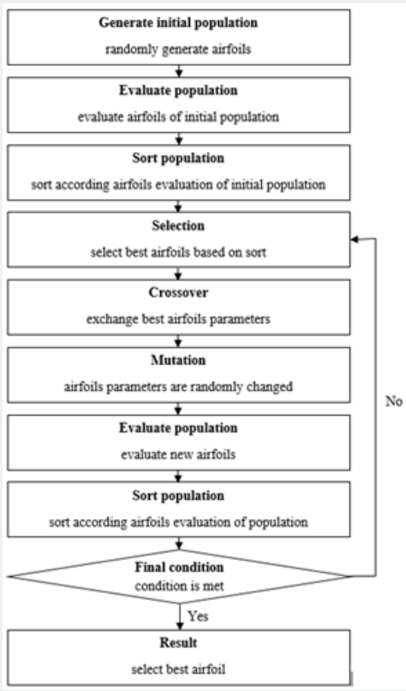

Figure 9: Evolution algorithm operations.

Crossover combines the parameters of the best aerofoils, which means the best evaluated. The aerofoil shape is subjected to the Xfoil calculation program. The result is a new population of aerofoils. The theoretical proof of the crossover correctness is based on theory of schemes (building block hypothesis). It assumes that combination of best parents (aerofoils) creates new children (aerofoils) better than parents (aerofoils). The highest qualities of parents (aerofoils) alive in their children (aerofoils). The most important is the part where the optimization crossover and mutates the aerofoils from the first part, while the second part is overwritten by the newly created aerofoils (Figure 10).

EA Application for cruise mission

For cruise mission is most important aerodynamic feature aerofoil drag having direct relation to fuel consumption. First the parameters are passed to Bezier-PARSEC parameterization.

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Bezier-PARSEC parameterization is combination of parameterization technique PARSEC and Bezier curves. The result of parameterization is aerofoil thickness and camber, from which the aerofoil shape is calculated. Once parameterization is passed, the Reynolds number and the angle of attack are added. Such data are inserted into program Xfoil, which uses panel methods to calculate fundamental aerodynamic parameters of aerofoil during cruise mission (Figures 11 & 12).

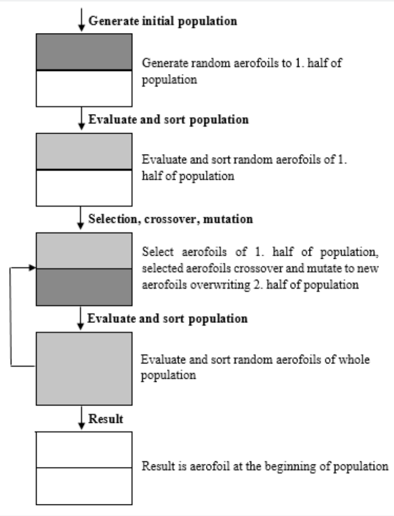

Figure 10: Evolution algorithm population.

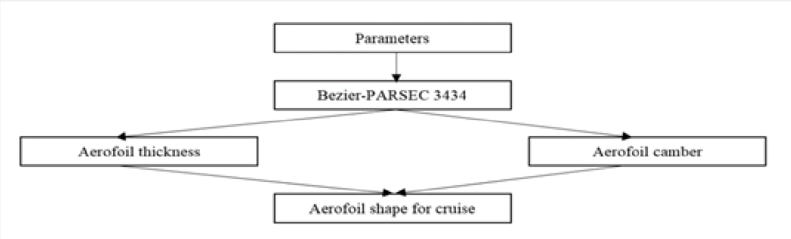

Figure 11: Shape generation.

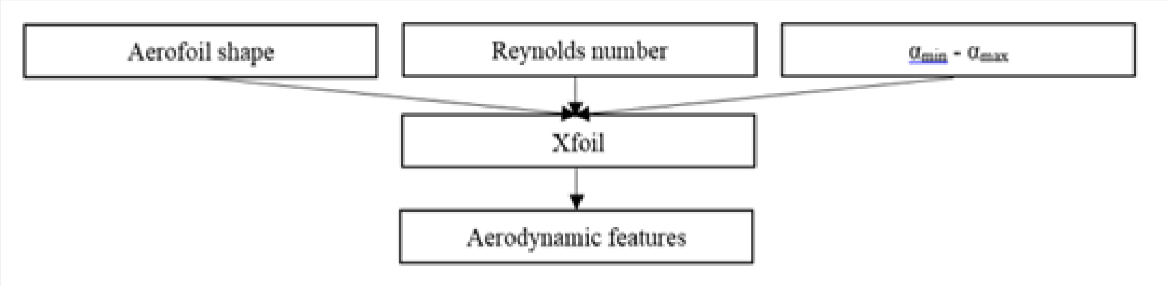

Figure 12: Obtaining aerodynamic features.

Direct Control Aerofoil Geometry (DCAG)

The DCAG developed mechanical device makes possible the change of curvature of aerofoil, and also aerofoil geometry with very simple application (the principle is illustrated in Figure 4). DCAG is based on the rotary principle, which makes it possible to define the curvature of aerofoil for every roll as well as defining the geometry in the variable parts of aerofoil (Figures 13-21).

DCAG application

This device is suitable for many applications. The application for wings can reach optimal aerodynamic features for every flight mission, increasing of lift resulting to STOL effect, higher maneuverability of aircraft, direct de-icing by skin micro rotations. Also, the device can be used for changing of wind turbines blade shapes, changing of water turbines blade shapes, for example,

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for the Francis and Kaplan turbines. Usage of device for turbines could increase efficiency. A quite different application is F1 cars. It would be possible to apply DCAG both the front and the rear wing to reach better accuracy and effective pressure regulation. These application examples are not a full list of all possible applications, but only a small sample.

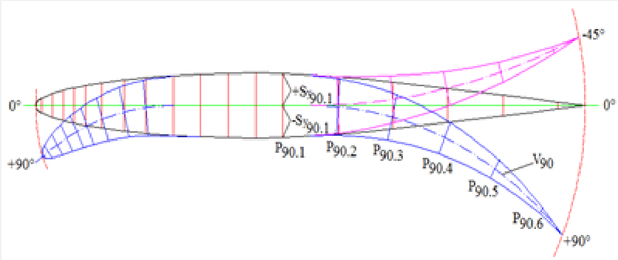

Figure 13: Expected geometry of aerofoil.

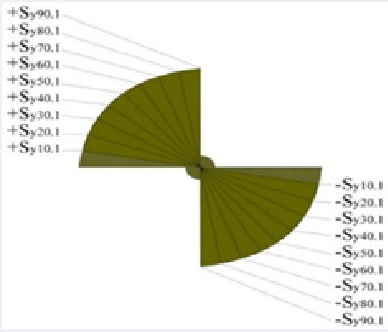

Figure 14: Transverse section P1.

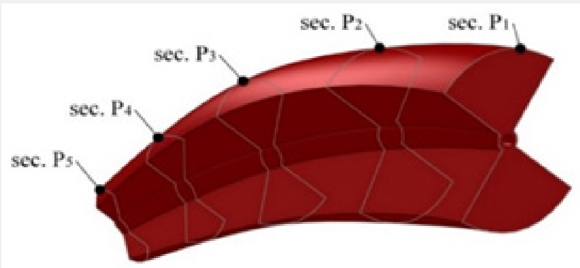

Figure 15: Retainer surface.

Figure 16: Revolution retainer view 1.

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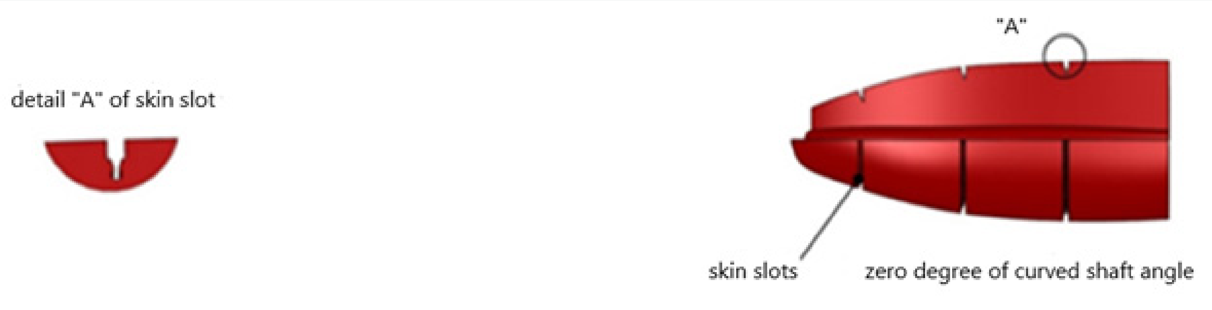

Figure 17: Revolution retainer view 2.

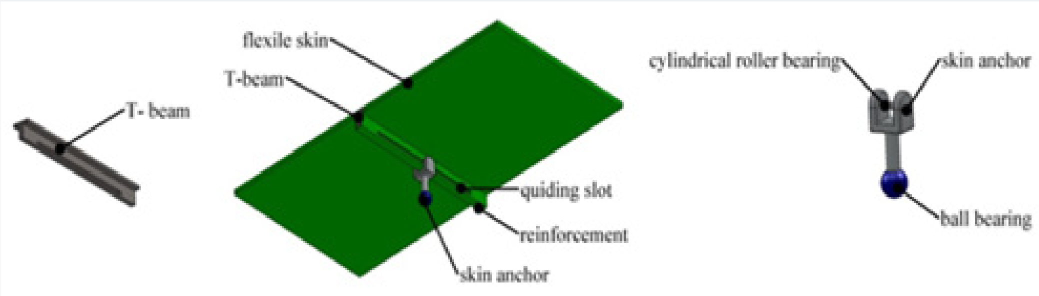

Figure 18: Skin.

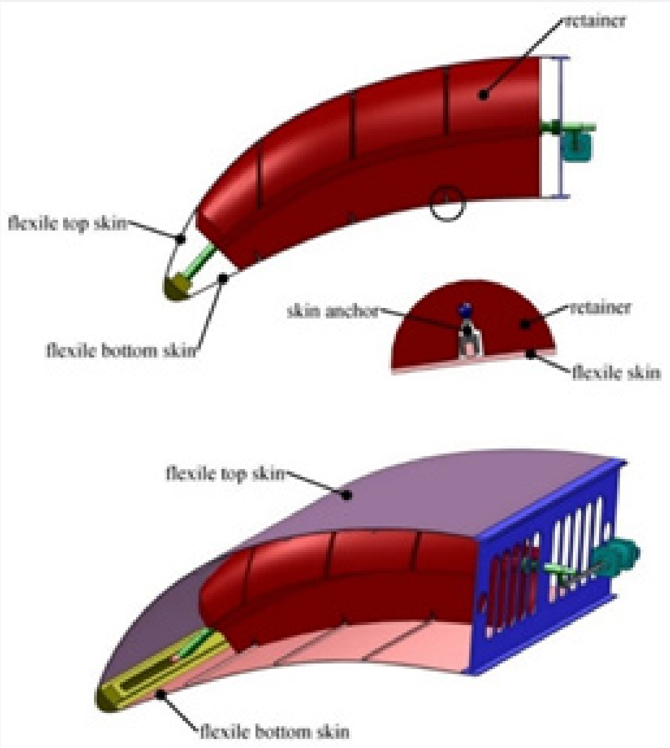

Figure 19: Device with skin.

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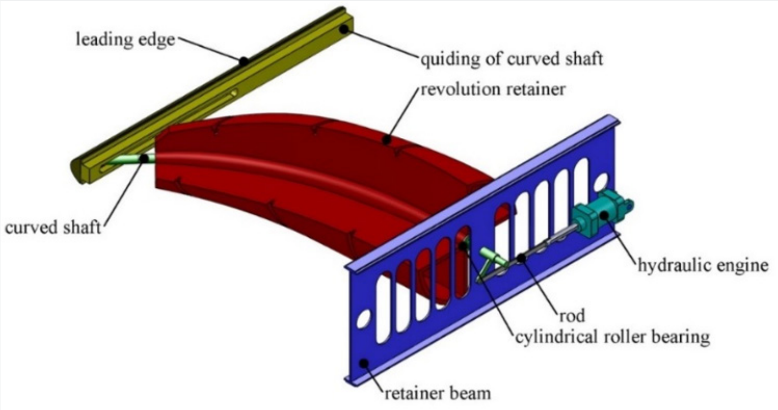

Figure 20: Final device assembly without skin.

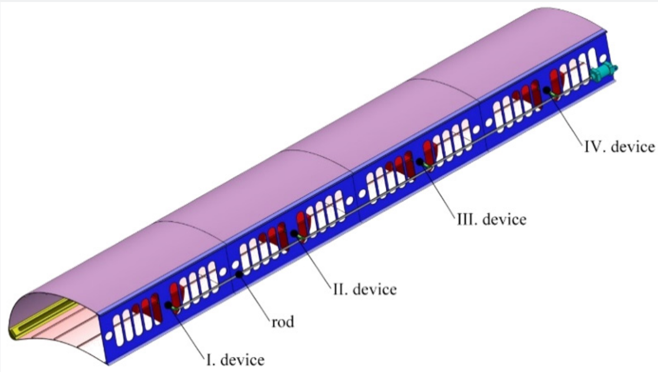

Figure 21: Resulting wing.

Aerofoil Aerodynamic Features Calculation for the Fitness Function

At present aerofoils are designed either by the inverse method or by a combination of direct and inverse method [12-14]. A panel method is often used for the inverse method, e.g. Xfoil by Mark Drely, but aerofoils are still being designed using the conformal transformation method from Richard Eppler, Franz Xaver Wortmann. The inverse methods used to solve the aerofoils by the panel method, but more complex methods can be used, e.g. finite volume method or finite element method such as ANSYS Fluent.

XFoil

XFoil combines compressibility correction with methods associated with viscous and non-viscous flows [11]. XFoil uses two basic equations, boundary layer retention and panel method. Accuracy can be improved by eg Euler or Navier-Stokes equations, but it would slow down the calculation [15,16]. Since 1970, aerodynamics has been very often used as a panel method, solving the potential flow in any general part of the aerofoil by a model based on discretization of the aerofoil contour using singularly connected straight panels with linear vortex distribution between the end points, as shown in Figure 22. [17-20]. XFoil can be run from the command line and interactively controlled through commands and functions offered by menus, or bat file can be created and sent to the program (Figure 23). Results of XFoil program calculation are lift, drag and moment coefficients for angles of attack range (Figures 24 & 25).

ANSYS fluent

ANSYS Fluent is a complex program used for computational fluid dynamics (CFD), especially for simulations solving fluid flow problems.

Physical models and their combinations in ANSYS Fluent, unlike Xfoil, are able to solve almost all problems in industry [21]:

a) aviation - airplanes, examples of air flow around wings, spaceships

b) land transport - improve car aerodynamics

c) medicine - blood flow in artificial heart, air flow during breathing

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d) chemical engineering - flow through pumps or tubes, combustion of coal in furnaces

e) energy engineering - increasing turbine efficiency, development of wind power plants

Multi-physical simulation allows to transmit the results of one simulation as input data to another simulation. Today, ANSYS Fluent is the most widely used CFD simulation software.

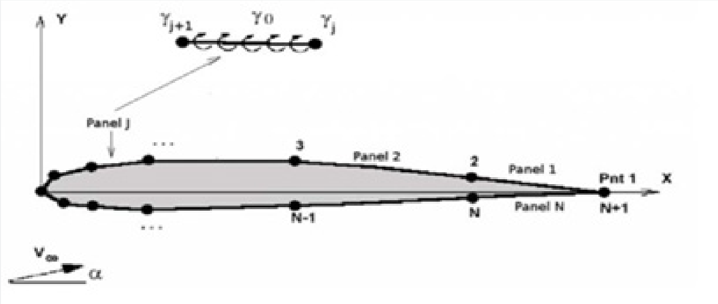

Figure 22: Potential aerofoil flow solution (panel method).

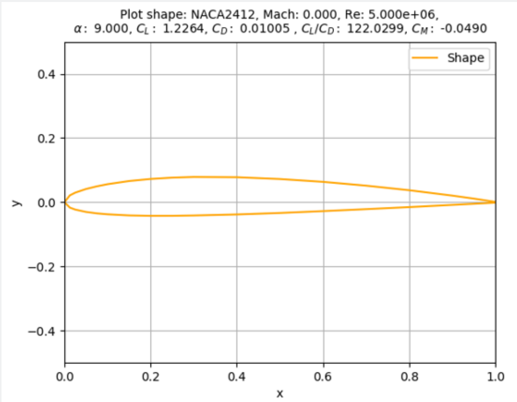

Figure 23: NACA 2412 aerofoil shape.

Results

The comparison of the NACA 2412 aerofoil shape [22,23] and optimized aero foil shape shows obvious differences between the shapes of the aerofoils, see Figures 23 & 26, which are reflected in different aerodynamic characteristics and features. Figures 27 & 28 show higher lift and lower drag of the optimized aerofoil during cruise flight mission. To check the results of the aerofoil optimization based on Xfoil the simulation with same aerodynamic conditions was done in ANSYS Fluent. The differences between Xfoil (based on panel model) and ANSYS Fluent (transition k-kl-omega model) results were in few percent (max. 4.43%) (Figures 29 & 30) (Table 1).

Table 1: Improvement of aerodynamic parameters of optimal and NACA 2412 aerofoil.

	Optimized Aerofoil	NACA 2412 Aerofoil	Improvements [%]
α [°]	6.000	9.000	-
CL [-]	1.67220	1.22640	36.35029
CD [-]	0.00561	0.01005	44.17910
C_L / C_D [-]	298.07487	122.02985	144.26389

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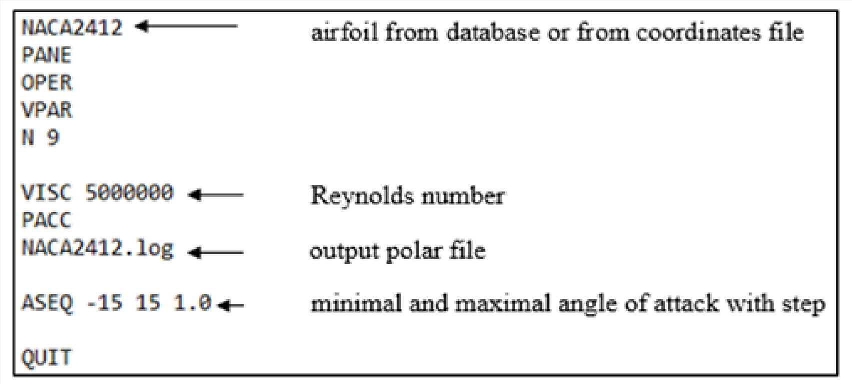

Figure 24: Sample bat file.

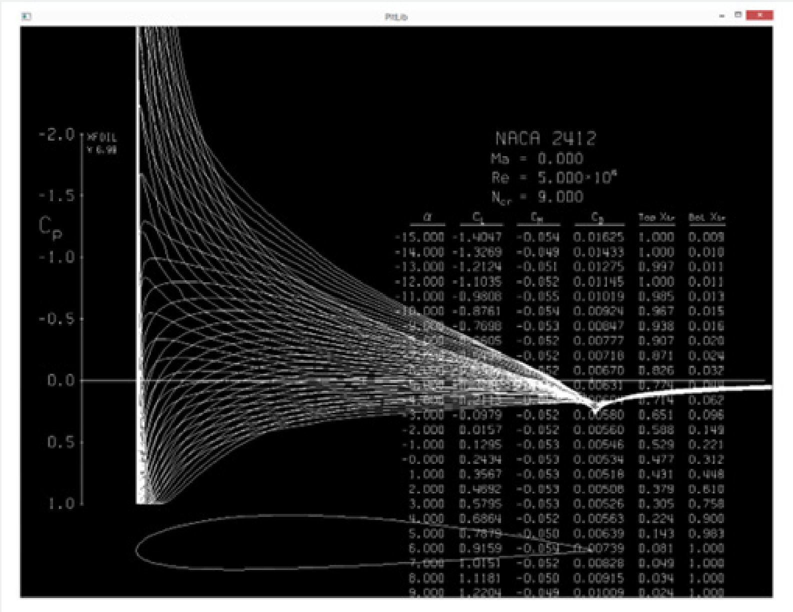

Figure 25: Lift, drag and moment coefficients in program Xfoil.

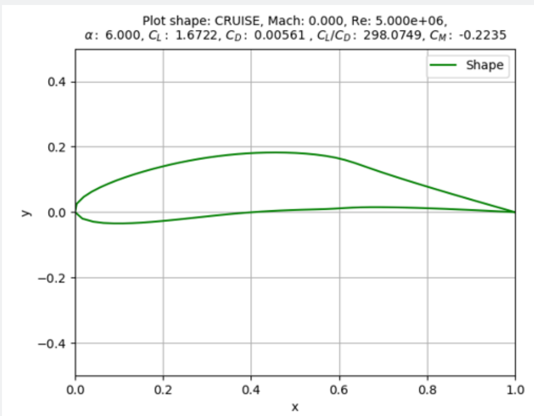

Figure 26: Optimized aerofoil shape.

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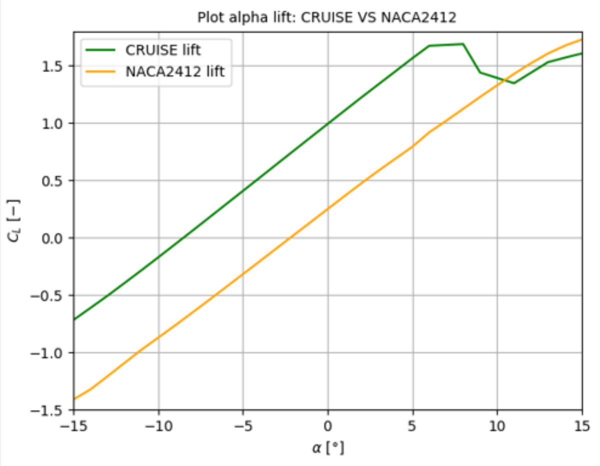

Figure 27: Aerofoils lift curves.

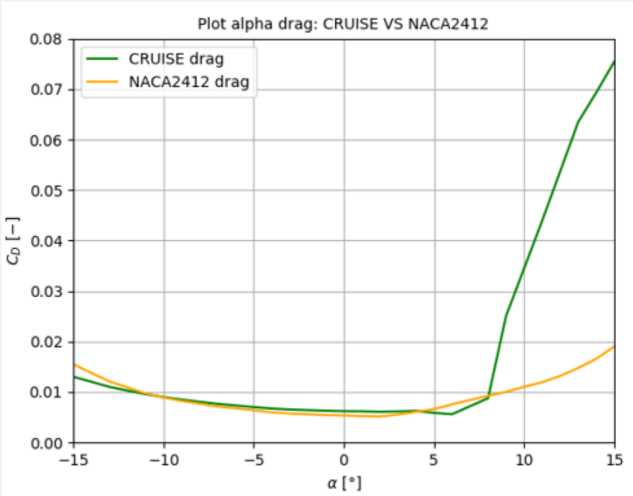

Figure 28: Aerofoils drag curves.

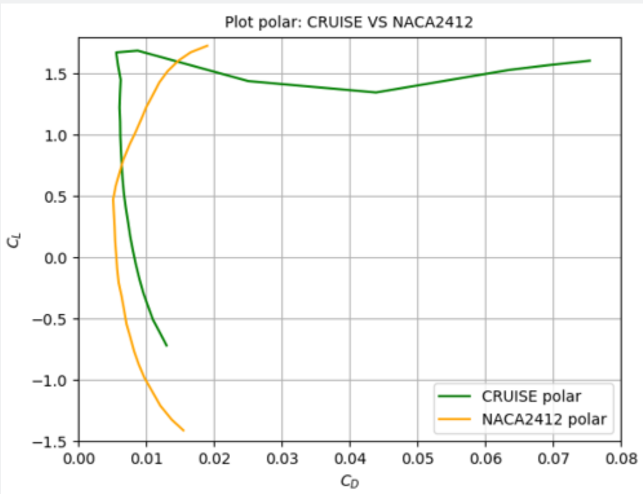

Figure 29: Aerofoil polars.

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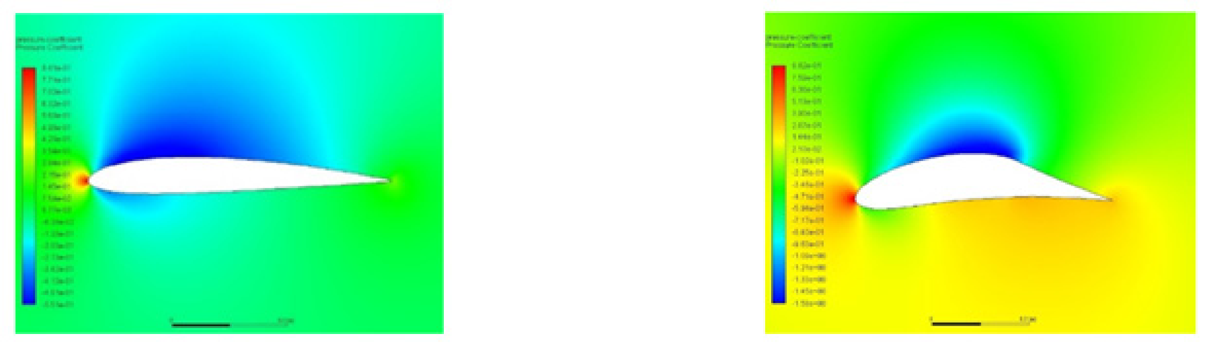

Figure 30: Pressure coefficients in ANSYS Fluent for angle of attack α=0o.

Improvements

New modified evolution algorithms (EA) are used with aerofoil parametrical model (Bezier-PARSEC 3434) to create a new aerofoil shape based on the parameter values generated by these new evolutionary algorithms. The aerody-namic parameters calculated by XFoil are then evaluated using the fitness function.

This new methodology of aerofoil shape calculation and created software achieved:

a) initial optimization conditions do not need the template, they are completely general

b) calculations quickly converge to the result (according to the set fitness function), compared to currently used calculations

c) optimized aerofoil calculations are fast, compared to currently used calculations

d) optimized aerofoil shapes have a very low aerodynamic drag during cruise mission

When optimization fitness function is focused to reach aerodynamic extremes, in some cases the flight has to be controlled by computer.

Morphing by Direct Control Aerofoil Geometry is suitable for many applications, which are mentioned bellow:

a) optimal aerodynamic features for every flight mission

b) massive increase of aerodynamic lift allowing STOL effect

c) because of combination of DCAG with various aerofoil geometry, a high maneuverability of the aircraft

d) direct de-icing by micro rotations of DCAG

Conclusion

The developed modified evolutionary algorithms introduce new inventions to aerofoil optimization:

a) conventional optimization starts by selection of existing aerofoil to be optimized and such selection is based on aerodynamics experience, but new modified evolutionary algorithms is based on a randomly generated first parent population, creating an independent and optimal configuration for optimization without need for any templates

b) Bezier-PARSEC 3434 aerofoil geometry model was used for optimization and because of it, the aerofoil can be parameterized for optimal aerofoil shape

c) calculations quickly converge to the result (according to the set fitness function), compared to currently used calculations

d) optimized aerofoil shapes have a very low aerodynamic drag during cruise mission

e) the optimized aerofoil reduces the environmental impact and is reflected in reduced operating costs

f) when based on aerodynamics experience, an existing aerofoil is selected and optimized, a new aerofoil optimization is created based on a randomly generated first parent population, creating an independent and optimal configuration for optimization without any templates

Bezier-PARSEC 3434 parameterization, XFoil program for calculation and new modified evolutionary optimization algorithms have not been used yet. The industrial application of the created software and the invention is very wide and in the case of aircraft technology brings the following basic advantages:

a) reduction of aerofoil aerodynamic drag based on calculation. As a result, fuel consumption is significantly reduced

b) improvement of aerodynamic characteristics of the wing for different flight missions resulting from the calculation

c) increasing of wing lift to values unreachable by known means based on calculation. As a result, this means a need of shorter runway length for take-off and landing (STOL characteristics). Reducing the airplane's landing speed results in better airplane safety and lower operating costs

The work results to optimization, which is many times faster in comparison to ordinary optimization, with minimum of input parameters (flight speed, chord length, range of angles of attack

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and fitness function). The optimized aerofoil can achieve the aerodynamic drag reduction up to 44% in comparison with NACA 2412 aerofoil. The optimized aerofoil can achieve significant fuel savings. The work was integrated into software design (approx. 15000 lines of source code in Python).

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