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Improving Initial Aerofoil Geometry Using Aerofoil Particle Swarm Optimisation

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Abstract
Advanced optimisation of the aerofoil wing of a general aircraft is the main subject of this paper. Meta-heuristic optimisation techniques, especially swarm algorithms, were used. Subsequently, a new variant denoted as aerofoil particle swarm optimisation (aPSO) was developed from the original particle swarm optimisation (PSO). A parametric model based on B-spline was used to optimise the initial aerofoil. The simulation software Xfoil was calculating basic aerodynamic features (lift, drag, moment).

Keywords: *Swarm Algorithms, Bezier-PARSEC Model, Aerofoil, Wing, Aerofoil Wing, Optimisation, Metaheuristics, Xfoil.*

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1 Introduction

The aim of the work is to optimise the aerofoil wing of a general aircraft. The advancement of aviation has always been linked to improved economic, environmental, and operational safety outcomes [20]. Thanks to the new algorithms of optimisations and recently developed software, previously unattainable results can now be reached. Because aviation technology represents a multidisciplinary and interdisciplinary area, the compromise between different disciplines demands is very difficult and thus requires taking into account a number of often conflicting requirements. Aerodynamics is a fundamental discipline for aviation and is closely related to the geometry of aerofoil. Aerofoil optimisation is necessary to find optimal aerofoil shape with optimal aerodynamic features [18].

To optimise the aerofoil, it is necessary to characterise the aerofoil by a few parameters denoted as parameterisation. The most important requirements for parameterisation are as follows: if possible, define the aerofoil geometry on as few parameters as possible, which affects the optimisation speed, selection of an initial aerofoil, which already has good evaluation of fitness function. The B-spline parameterisation [16] based on the control points meets the mentioned requirements. The most important features for good optimisation are the speed of convergence, maintaining diversity, and avoiding elitism. The fitness function is evaluating the division of aerodynamic lift to drag, searching for the average highest division.

Original particle swarm optimisation (PSO) was modified to many optimizing liaisons (MOL) optimisation, which is base to aerofoil particle swarm optimisation (aPSO). Aerofoil particle swarm optimisation is used to implement B-spline parameterisation for initial aerofoil optimisation. The results from the mentioned optimisation (aPSO) are compared with the results of CFD ANSYS Fluent. The aerofoil with the lowest aerodynamic drag, reached by optimisation, reduces fuel consumption during cruise mission. This has a direct impact on flight-prices and also on the environment. The highest aerodynamic lift increases the safety of aircraft during take-off and landing [7]. The fitness function is characterised by the division of aerodynamic lift to drag, keeping together high aerodynamic lift with low aerodynamic drag. Bio-inspired algorithms are known for their ability to solve complex optimisation problems. Aerofoil optimisation has been solved by several authors. Derksen and Rogalsky [3] used genetic algorithms, while Lampinen and Zelinka [9] applied differential evolution. The mentioned evolutionary algorithms were compared with swarm algorithms. Swarm algorithms achieved better results, especially many optimizing liaisons (better by tens of percent).

2 Project ATR-42-4

ATR-42-4 [5, 8, 6, 14] was one of the first aircrafts with applied aerofoil optimisation. The part of the upper surface of the aerofoil was elastic, allowing deformation by two actuation points (Fig. 1).

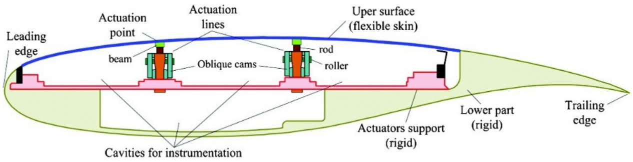

Figure 1: Project ATR-42-4.

Genetic algorithms (GAs) were used. Each individual in the population was defined by two real values, representing the stroke of the action members. The fitness function was focused on minimizing aerodynamic drag [20, 10]. Modifications of the part of the upper surface are defined by cubic splines (Fig. 2).

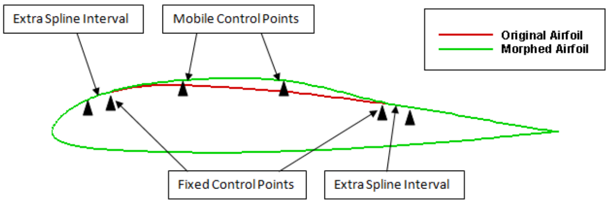

Figure 2: Aerofoil shape optimisation.

The calculation of the aerodynamic features of aerofoil was performed by the Xfoil general simulation program, which calculates the lift and drag values of the aerofoil. Input data to the Xfoil are as follows: Mach number, Reynolds number, angles of attack, and aerofoil data file (x, y coordinates).

As a result of this modification of the aerofoil geometry, the drag coefficient was reduced by up to 26.73%. Reduction of aerodynamic drag leads to a reduction in fuel consumption by more than 20%. At the same time, the lift increased significantly, especially in the range of small positive and negative angles of attack.

3 Methods

3.1 Aerofoil Geometry Model Selection

It is evident that aerofoil geometry model selection is fundamental for the whole process of optimisation [19]. One way to characterize the aerofoil geometry is to use control points. By manipulating the control points [2] the geometry of the aerofoil and thus also the aerodynamic features of the aerofoil change. Control points of aerofoil NACA 2412 are used, and the shape is defined by B-spline curve (Fig. 3).

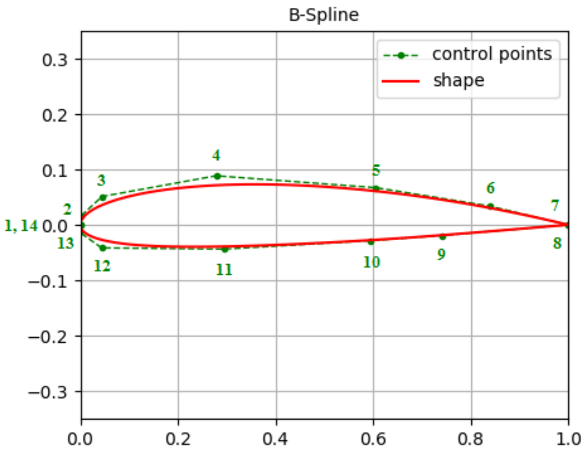

Figure 3: NACA 2412 aerofoil based on 14 control points.

Aerofoil particle swarm optimisation (aPSO) was used to optimise the initial aerofoil. The fitness function searches for the average division of lift to drag in a certain interval of angles of attack, rather than finding just one angle of attack with the highest division.

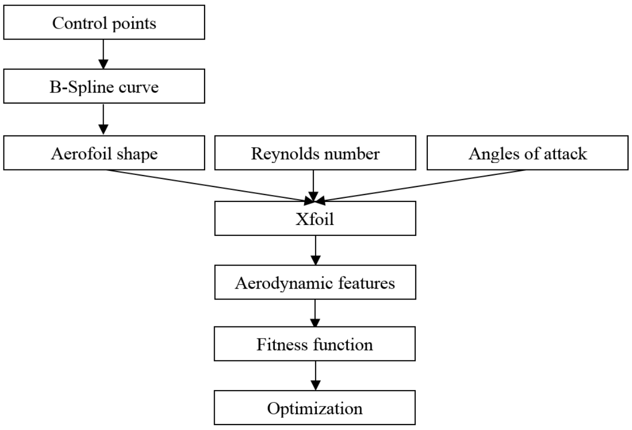

Figure 4: Flowchart of calculation of aerodynamic features based on control points.

The flowchart (Fig. 4) demonstrates how the NACA 2412 aerofoil is optimised. First, the initial 14 control points from the original aerofoil are set. Second, the B-spline curve is used to generate an aerofoil shape from those control points. The generated aerofoil shape is represented by a set of coordinates saved in a text form file. Finally, the Xfoil program was used to calculate the pressure distribution on the aerofoil and hence lift and drag characteristics [4].

Input data to Xfoil program are given by the coordinates, specifying the shape of the aerofoil, Reynolds number, and angles of attack. Output from Xfoil program is a text form file with aerodynamic features corresponding to input coordinates and settings. For all iteration the vertical positions of control points are modified by optimisation and a new shape, with new aerodynamic features, is generated.

3.2 Aerofoil Fitness Function

The wider cruise mission is defined by the range of angles of attack, in this case 3°-9°. For optimisation with the initial aerofoil, NACA 2412 was chosen [1, 11]. The fitness function searches for the maximum average aerodynamic lift to drag division in the range of the wider cruise mission.

To compare the aerodynamic features of both aerofoils, calculation conditions must be same, the swarm size is set to be 25 aerofoils, the Reynolds number 5.0e+06 and angles of attack from 3° to 9°.

The optimised aerofoil is related to the initial aerofoil and inherits the features of the original aerofoil.

3.3 Many Optimizing Liaisons (MOL)

It is important to note, that many optimizing liaisons (MOL) optimisation is based on the original particle swarm optimisation (PSO) [1, 11, 17]. Particle swarm optimisation (MOL) was invented and first applied by Marcus Pedersen [15].

This optimisation eliminates the best found position of the particle *pBest* by the acceleration coefficient c_1

Algorithm 1 Pseudocode of aerofoil particle swarm optimisation (aPSO) application

```
best swarm evaluation = 0
$gBest = []$
for each aerofoil $i$ do
    generate array of speeds $v_i$ and control points $x_i$ from initial to actual aerofoil $i$
end for
$t = 0$
while $t <$ maximum iterations do
    for each aerofoil $i$ do
        new evaluation of aerofoil $i = 0$
        while new evaluation of aerofoil $i = 0$ do
            if best swarm evaluation <> 0 then
                update array of speeds $v_i$ of aerofoil $i$: $v_i = \omega v_i + c_2 r_2 (gBest - x_i)$
                update array of control points $x_i$ of aerofoil $i$ : $x_i = x_i + v_i$
                new evaluation of aerofoil $i$ is calculated by fitness function: $\sum_{j=1}^{N} (C_L/C_D)_j/N$
            end if
            if new evaluation of aerofoil $i = 0$ then
                generate array of speeds $v_i$ and control points $x_i$ from initial to actual aerofoil $i$
            end if
        end while
        if new evaluation of aerofoil $i$ <best swarm evaluation or best swarm evaluation = 0 then
            set best swarm evaluation to new evaluation of aerofoil $i$
            set $gBest$ to array of control points $x_i$ of aerofoil $i$
        end if
    end for
    $t = t + 1$
end while
```

being 0. The particles are then randomly selected in the inner loop. The result is a simpler implementation that works as well as the original version of particle swarm optimisation, if not better [15]. From many optimizing liaisons (MOL) optimisation was developed general aerofoil particle swarm optimisation (aPSO).

3.4 Aerofoil Particle Swarm Optimisation (aPSO) Application

When applied, the classical array of positions and speeds is replaced by a one dimensional array of control points and speeds. Also the term aerofoils is used instead of particles [13].

Calculate array of speeds of aerofoil:

$$v_i = \omega v_i + c_2 r_2 (gBest - x_i)$$

Calculate array of control points of aerofoil:

$$x_i = x_i + v_i$$

Where:

i	index of the individual aerofoil in the swarm
v_i	array of speeds of aerofoil i
x_i	array of control points of aerofoil i
$gBest$	best array of control points of the swarm
ω	inertia weight constant
c_2	acceleration coefficient
r_2	random number between 0 and 1

Evaluate by fitness function:

$$\sum_{j=1}^{N} (C_L/C_D)_j/N$$

Where:

N	all optimised angles of attack
C_L	aerodynamic lift
C_D	aerodynamic drag

3.5 Comparison of NACA 2412 Eerofoil and Optimised Aerofoil

Many optimizing liaisons optimisation is used to optimise initial aerofoils with a weight of inertia $\omega = -0.2$ and an acceleration coefficient $c_2 = 2.8$. The range of angles of attack used for optimisation is from 3° to 9°, but the figures are showing the range from -15° to 15° just to demonstrate the behaviour of the aerofoil in the usual range of a cruise mission.

4 Results

Aerofoil particle swarm optimisation (aPSO) with initial aerofoil optimisation, in this case NACA 2412, is used to optimise the wider cruise mission, which is defined by a range of 3°-9° of angles of attack.

The fitness function searches for the maximum average aerodynamic lift to drag division in the range of

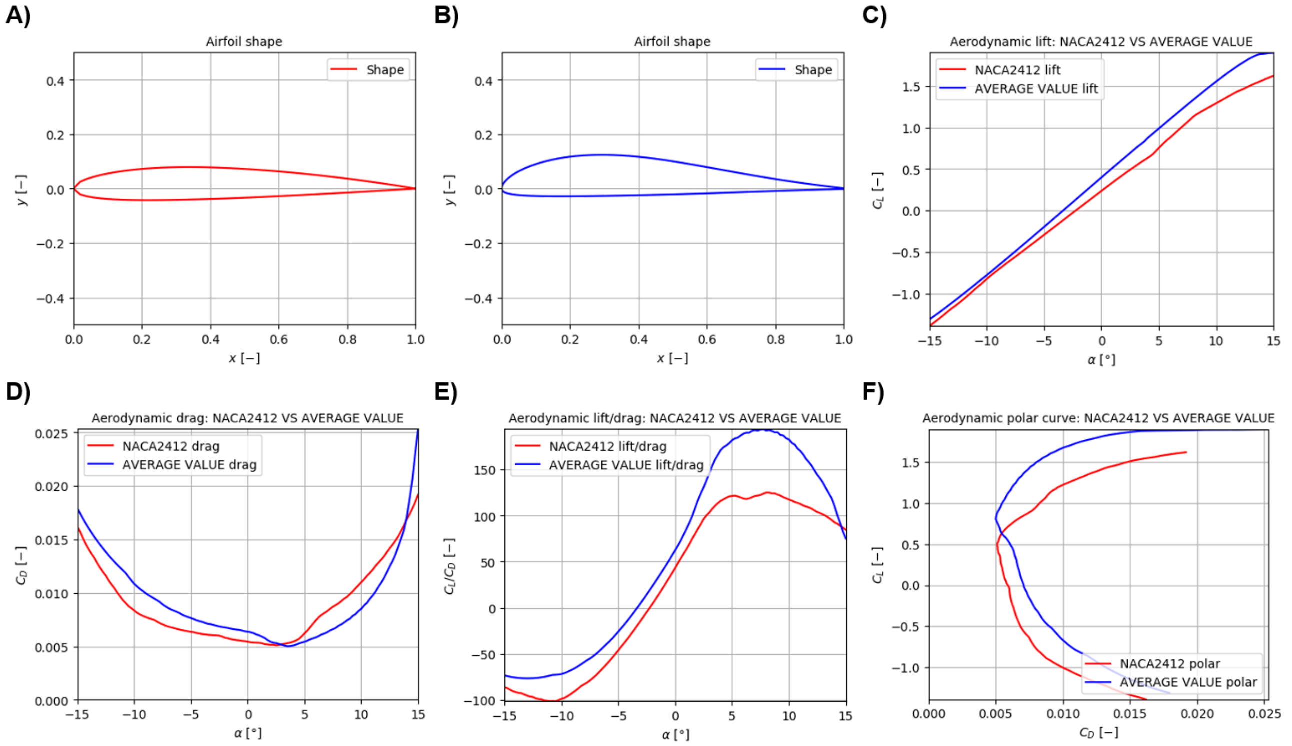

Figure 5: Aerofoil features (A) Shape of NACA 2412 aerofoil (102 coordinates).(B) Shape of optimised aerofoil (102 coordinates).(C) Aerodynamic lift, C_L.(D) Aerodynamic drag, C_D. (E) Aerodynamic lift to drag, C_L/C_D. (F) Polars, C_L and C_D.

Table 1: Comparison of aerodynamic features of NACA 2412 and optimised aerofoil.

	α	C_L	C_D	C_L/C_D	C_M
NACA 2412	3°-9°	0.87	0.0073	119.8	- 0.045
Optimised aerofoil	3°-9°	1.09	0.0060	183.2	- 0.055
Improvements		+25.2%	-18.1%	+52.9%	+22.1%

wider cruise mission. This is used to find better aerodynamic features of an existing aerofoil.

The optimisation defines the shape of the aerofoil based on vertically tuning the control points chosen from the initial aerofoil. These are then modified to achieve better aerofoil geometry with correspondingly better aerodynamic features.

The advantage of using the optimisation of initial aerofoil is inheritance of the good aerodynamic features from initial aerofoil to optimised aerofoil.

Because the NACA 2412 aerofoil has safe features, also optimised aerofoil partially inherits those features and so should be safe, as it can be seen from (Fig. 5) both aerofoils have very similar trends.

If aerodynamic features of the optimised aerofoil guarantee safety, there is no need for computer control during the flight. The resulting average reduction in aerodynamic drag is reduced by 18.10%, the lift and drag division is increased by 52.94% compared to the initial aerofoil NACA2412.

5 Conclusion

The work is focused on optimising of the geometry aerofoil wing of a general aircraft. Optimising the geometry of the aircraft aerofoil has an important role in the aerodynamics and economy of aircraft operation. The fundamental importance and benefit of the research is the creation of a new, unique algorithm to optimise the geometry of the selected aerofoil.

Aerofoil particle swarm optimisation (aPSO) achieves better results than reached by aerofoil evolutionary algorithms.

Parameterisation based on the B-spline was used to represent the geometry of the selected aerofoil. To characterize the geometry of the selected aerofoil, control points were used, with the need to select the initial aerofoil representing the initial shape. The NACA 2412 aerofoil was selected.

An evaluation function (fitness function) was created to select aerofoil with best aerodynamic features. The searched aerofoil should have the maximum average aerodynamic lift to drag division.

Optimisation of the aerofoil particle swarm optimisation achieves very good results, with the best results for the size of swarm 25, with a weight of inertia $\omega = -0.2$ and an acceleration coefficient $c_2 = 2.8$. The optimisation is based on the many optimizing liaisons (MOL) optimisation variant, which was also modified to use B-spline parameterisation.

The benefits of the work in terms of aerodynamics are finding the minimum aerodynamic drag compared with initial aerofoil NACA 2412.

During a wider cruise mission flight in the range of 3°-9° angles of attack, the reduction of aerodynamic drag by 18.10% compared to the selected NACA 2412 aerofoil was achieved.

This aerofoil optimisation is directly followed by the control of its geometry according to my invention [12]. It is possible to change the shape of the aerofoil (morphing) in flight so that the behaviour of the aircraft is safe and at the same time economical.

By comparing the results obtained from the aerofoil optimisations (only with part of upper surface morphing) of the ATR-42-4 aircraft, the validity of the results is quite evident.

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