Application of Evolutionary Algorithm on Aerodynamic Wing Optimisation

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Abstract: Search for safety and high efficiency is the driving force in the aerospace industry. This paper reports on application of a relatively new and very promising evolutionary algorithm SOMA with the intent to answer the question on optimal wing geometry. We describe aerodynamic model of the wing, the evolutionary optimisation process and results we obtained. In this contribution present a modern, high performance global optimisation algorithm applied on real engineering application resulting into a set of evolutionary-designed wings which we developed in cooperation with a leading civil aircraft design bureau and manufacturer.

Key–Words: Evolutionary algorithms, Aerodynamics, Optimisation

1 Introduction

Development of an aerodynamic shape optimisation methods is important to improve design efficiency in today's competitive environment for the commercial aircraft industry. Aerodynamic-wise optimal shape of an aircraft does not only delight an expert's eye, it is a crucial factor affecting the plane performance and thus its success on the world markets.

To optimise a shape of a wing does not only mean to reduce drag and maximise its lift. There are also other factors that influence the fitness of a wing for a particular aeroplane. In our model we focused on the shape of the lift curve along the wing semi-span, which had to fulfill some requirements in order to ensure the wing has good stall characteristics and overall performance.

To perform a thorough optimisation, one has to dispose of a powerful tool. For this certainly very challenging problem we have such a one at hand - the Self-Organising Migrating Algorithm - SOMA [1]. SOMA is a very modern optimisation algorithm, which in many cases of test function benchmarks and also real-world optimisation tasks outperforms other evolutionary-based optimisation techniques. Successful applications like active compensation of disturbing signals on a Langmuir probe measuring properties of RF-driven plasmas [2], symbolic regression, a robot's trajectory optimisation, real-time deterministic chaos control [3], neural network synthesis, combustion engine optimisation [4] and relay node placement in energy-constrained networks [5] shown very decent performance of this algorithm.

2 Wing optimisation

Modelling of aerodynamics is a complex problem and there are various approaches how to solve it. Authors of many present papers, e.g. [6, 7], use the widely-used CFD modeling to achieve best possible simulation results. There are also other studies like [8] and [9] in which is the aerodynamic shape optimisation treated as a control problem. In this case, the wing is treated as a device which controls the flow to produce lift with minimum drag, while meeting other requirements such as low structure weight, fuel volume and stability and control constraints.

In general, methods using CFDs are very accurate, but unfortunatelly, they are extremely expensive in terms of calculation time. In combination with evolution algorithms, that typically need high number of evalutions, are CFD models not very suitable. Therefore, instead of using models with such precision, we replace them by other approaches whose evaluation is less CPU-intensive but they still model the reality very well. One such application is described in [10].

For our purposes of optimisation by means of an evolutionary algorithm, we decided to use simple predictors that are very quick to evaluate and still describe the properties in which we are interested with very high precision. The following section outlines the model we used for the wing optimisation.

2.1 Optimised model

Based on the Zhukovsky theorem (described in [11]), influence of an infinite wing put into a flow of liquid on this liquid can be substituted by influence of a potential vortex. The vortex system can be divided into three main parts: the starting vortex, the trailing vortex and the bound vortex system (the last one is also denominated as a lifting vortex). The total vortex system associated with a wing form a complete vortex ring that satisfies all physical laws. The starting vortex, however, is soon left behind and the trailing pair stretches effectively to infinity as steady flight proceeds. For practical purposes the system consists of the bound vortices and the trailing vortex on either side close to the wing. This three-sided vortex has been called the *horseshoe vortex*.

Study of the completely equivalent vortex system is largely confined to investigating wing effects in close proximity to the wing. For estimation of distant phenomena the system can be simplified to a single bound vortex and trailing pair, known as the *simplified horseshoe vortex*. Intensity of a vortex, i.e. total amount of vorticity passing through any plane region within a flow field, is called *circulation* (Γ).

Aerodynamic model of the wing is based on the Glauert's solution of Prandtl's equation. The Prandtl's equation (1) [12] describes circulation Γ at any section z along the wing span in terms of the aerofoil parameters (two dimensional lift slope a_∞, incidences α and α_0). The solution of this equation cannot be found analytically for all points along the span but only numerically at selected spanwise stations and at each end of the wing. Having this solution we are able to calculate aerodynamic characteristics of the wing.

$$\frac{2\Gamma(z)}{c(z)a_\infty} = v(\alpha - \alpha_0) + \frac{1}{4\pi}\int_{-s}^{s} \frac{d\Gamma/dz}{z - z_1} dz \qquad (1)$$

Comparing to [12], instead of using linear lift slope characteristics for computing local lift coefficient, we replaced them by full non-linear aerofoil lift and drag characteristics to provide more accurate results, especially in cases close to critical angle of attack.

The wing was divided into three sections (see Figure 1) to enable us to manipulate with the following geometric properties of the wing:

- Section intermediate point 1 - y coordinate of transition between sections 1 and 2,
- Section intermediate point 2 - y coordinate of transition between sections 2 and 3,
- Chord length 1 - length of the root chord of the wing (profile cut next to the fuselage),
- Chord length 2 - length of the chord on the transition between sections 1 and 2,
- Chord length 3 - length of the chord on the transition between sections 2 and 3,
- Chord length 4 - length of the tip chord,
- Twist 1 - geometric twist of the root chord,
- Twist 2 - geometric twist of the chord between sections 1 and 2,
- Twist 3 - geometric twist of the chord between sections 2 and 3,
- Twist 4 - geometric twist of the tip chord,
- Wing span,
- Profile 1 - aerofoil type root the root cut,
- Profile 2 - aerofoil type for cut between section 1 and 2,
- Profile 3 - aerofoil type for cut between section 2 and 3,
- Profile 4 - aerofoil for the tip cut.

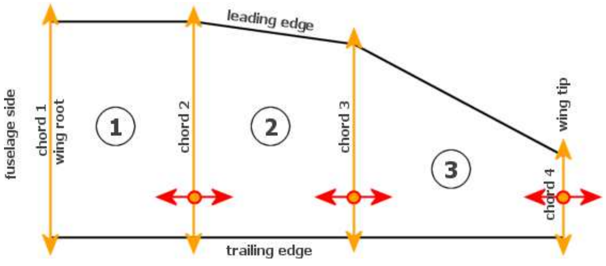

Figure 1: Modified parameters of optimised wing

The ranges of optimised parameters were set according to the requirements for each particular aeroplane. Coordinates of section intermediate points were set between 1 eter and the wing semi-span, chord lengths limited between 0.1 and 2 meters (however, the root chord length was in most cases determined by dimensions of the centroplane), geometric twist of the profiles represents absolute rotation of the particular cut against the plane fuselage. Wing span range is typically given by the aeroplane loading, for example for ultralights it was set between 7 and 12 meters. There were two available models of aerofoils for parameters 12-14 LS0417MOD and MS0313.

In all simulations we calculated the wing characteristics at 32 stations along the wing semi-span and assumed conditions of steady flight with angle of attack of 4 degrees.

The following computed output parameters were to be minimised:

- induced drag,
- surface friction
- overall wing area
- difference $C_L - 0.9 * C_{LMax}$ in 70% of semi-span,
- difference $C_{LMax} - C_L$ in $y = \langle 0, 40 \rangle$ of semi-span.

The last two items represent requirements on shape of the lift curve. To meet the requirements on wing stall characteristics, there must be at least 10% reserve of lift on the ailerons when the flow on root part of the wing is starting to separate (air flow separates from the wing at high angles of attack or low speeds; the value of critical angle of attack and minimum speed is given by used aerofoils). The second requirement maximises the overall lift of the wing.

The resulting computation of fitness is represented by weighted sum of minimised parameters:

$$\begin{aligned} costValue &= inducedDrag \cdot 100 \\ &+ frictionDrag \cdot 100 \\ &+ S/10 + 40pDiff \cdot 100 \\ &+ 70pDiff \cdot 100 + penalisation \end{aligned} \tag{2}$$

There is one additional requirement on the wing expressed by the *penalisation* value. It encapsulates the condition

$$S \cdot C_{LMax}(wing) \geq k, \quad k = \frac{2mg}{\rho v^2}, \tag{3}$$

where S is the wing surface, C_{LMax} the maximal lift of the wing, m stands for weight of the airplane, $g = 9.81$, ρ represents air density and v denotes velocity. It is desired to keep $S \cdot C_{LMax}$ as close as possible to k but not below.

The stall properties of the wing (requirements on shape of the lift curve) are computed at stall speed given by FAA directives (45 knots in our case) and the other properties at maximal speed of steady level flight (given by construction of particular aeroplane).

3 Experiments and Results

In our experiments we considered three different sets of contraints for the optimised model. These limitations were bound to type of the airplane for which the wing was designed - mostly determined by the plane's purpose and its construction. Our first goal was to propose modification of a wing design for the new generation of currently manufactured ultralight airplane - the SportStar SL. The second model configuration was adjusted to fit the four-seated VUT-100 Cobra, which was currently in the phase of prototyping and gave us some more (although still limited) manoeuvring space. The third concept stands for a clear sheet design, where there were no initial constraints limiting the evolutionary process. Due to limited space, in the following text we present only results of the VUT-100 SuperCobra wing optimisation. As mentioned above, the other wings variations were determined by different limitations and thus resulted into slightly different geometries and configurations.

3.1 VUT-100 Cobra wing optimisation

VUT-100 Cobra is an all-metal four-seat aircraft coming to serial production very soon. We decided to compare the already designed wing to a wing optimised by SOMA. The constraint conditions of the wing were as follows.

1. Wing consists of 3 sections,
2. length of chords 1 and 2 fixed at 1.597m (centroplane section),
3. maximum wing-span 12m,
4. y coordinate of chord 2 fixed at 1.25m (centroplane section length),
5. y coordinate of chord 3 can vary between 3m and half wing-span,

6. geometric twist of chord 1 fixed to 0, chord 1 allowed between -1 and +1 degree,
7. twist of chord 3 ranges between -3 to +3 and twist of chord 4 (tip of the wing) between -6 and +6 degrees,
8. LS01417MOD aerofoils are used for chords 1 and 2, types of aerofoils for chords 3 and 4 are optimised,
9. $S \cdot C_{LMax} \geq 20.8$ and
10. stall speed 45 knots, maximum speed 120 knots

Values obtained from the optimisation process can be seen in Figure 2, Table 1 and Table 2.

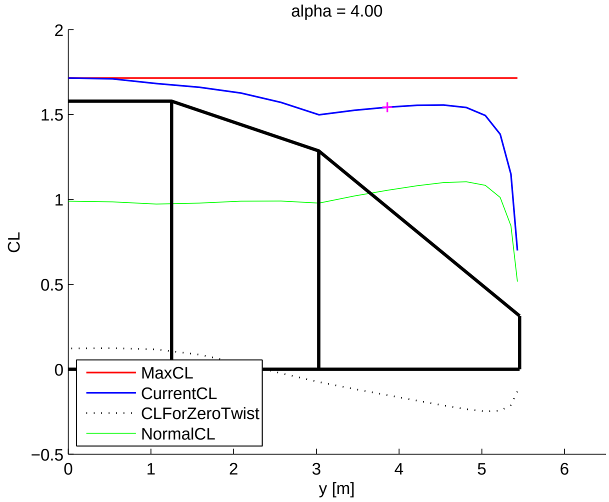

Figure 2: VUT-100 Cobra: shape of the evolved wing and its lift characteristics

wing area	=	12.93 m^2
C_{LMax}	=	1.59
$S \cdot C_{LMax}$	=	20.9
wing C_L	=	0.23
friction drag	=	0.01
induced drag	=	0.01

Table 1: VUT-100 Cobra: properties of the evolved wing

Let us explain the lift diagrams: *MaxCL* (red) stands for maximum lift of the wing. This value is given by the maximum lift of used aerofoils. The *CurrentCL* (blue) represents current state of lift distribution along the span. By increasing the angle of attack this curve changes its shape according to actual state. *CLForZeroTwist* describes spanwise lift for the case where the wing is under such an angle of attack that it has zero lift. This curve shows the influence of geometric twist on lift of the wing. And finally, the *NormalCL* curve (green) symbolises lift normalised to 1 at the root profile. By multiplying this value on selected station along the span by local lift coefficient, we get value of current lift. Small cross (magenta) in 70% of the wing semi-span indicates the 10% reserve of lift on the ailerons. Curve of the current CL must go through this point to ensure good stall characteristics of the wing.

section intermediate point 1	=	1.250 m
section intermediate point 2	=	3.029 m
chord length 1	=	1.579 m
chord length 2	=	1.579 m
chord length 3	=	1.2855 m
chord length 4	=	0.3139 m
wing span	=	10.913 m
twist 1	=	0°
twist 2	=	0.4691°
twist 3	=	-3.0000°
twist 4	=	-4.9685°
aerofoil 1	=	LS0417MOD
aerofoil 2	=	LS0417MOD
aerofoil 3	=	LS0417MOD
aerofoil 4	=	LS0417MOD

Table 2: VUT-100 Cobra: overview of the optimised wing parameters

As you can see, the optimisation process tends to evolve wings of high aspect ratio. This trend is mainly supported by the fact, that a wing with these characteristics has significantly lower values of drag (from the theory of aerodynamics infinite wings have zero drag). By demanding minimisation of the wing area (the $S \cdot C_{LMax}$ condition) and drag we force the evolutionary algorithm to make wings more slender and longer.

In the folowing paper [13] we compare the optimisation performance of SOMA and Differential Evolution (DE). DE is considered to be significantly more powerful optimisation algorithm than its predecessors like GA, PSO and others. Our experiments on both the test functions and real engineering problems indicate, that SOMA in many of the test cases considerably outpeforms all of these genetic/evolutionary algorighms.

4 Conclusion

Evolutionary algorithms based on principles of natural selection belong to very efficient methods of global optimisation. They use mechanisms inspired by biological evolution: reproduction, mutation, recombination, natural selection and survival of the fittest. Evolutionary algorithms perform consistently well approximating solutions to all types of problems and are able to find a feasible solution of many engineering problems in a reasonable time.

In this paper we presented application of a new evolutionary algorithm to aerodynamic optimisation of wing geometry for an aeroplane being prepared for production in the Evektor company, a leading civil aircraft producer in the Czech Republic. There were 15 optimised parameters minimising induced drag, surface-friction drag and overall wing area. Furthermore, to meet the directives on wing stall characteristics, there was requirement on shape of the lift curve. Results obtained for various wing configurations meet the desired wing parameters and support assumptions made by experts on aerodynamics. Wings evolved by SOMA tend to be of high aspect ratio with high values of lift and low drag. Created aerodynamic model together with developed optimisation software will be used as a requisite for future wing design in the company.

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