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Morphing wing airfoil optimization for small unmanned aviation vehicle

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Abstract: Modern small unmanned aerial vehicles (UAVs) perform a wide range of missions, requiring high efficiency in various, often conflicting, flight conditions. Conventional airfoils, optimized for a single specific condition, exhibit suboptimal performance in others, limiting the overall flight capabilities of the vehicle. A promising solution to this problem is the use of a morphing wing, capable of changing its shape in flight. This paper presents a simplified method for the multi-objective optimization of an airfoil for such a morphing wing. To overcome the computational complexity of the classical Pareto front approach, especially with a large number of flight conditions, the multi-objective problem was reduced to a single-objective form. This was achieved using the weighted sum method, where the objective functions (drag coefficients for each flight condition) were normalized relative to their reference values. The weights were calculated based on a physical parameter – the Reynolds number – enabling the optimizer to prioritize the most important cruise regime. The airfoil geometry was parameterized using the Class-Shape Transformation (CST) method, and for fast and accurate aerodynamic calculations, the NeuralFoam tool, based on physics-informed machine learning, was used. The study solves two optimization problems: for two and four flight conditions. The results of the two-point optimization are in good qualitative and quantitative agreement with data obtained independently by more complex methods. Results demonstrate that employing an idealized curvature adaptation mechanism enables the compromise airfoil to achieve 82.7–87.5% of the aerodynamic efficiency of reference airfoils, each optimized for a single specific condition. The proposed method demonstrates a significant reduction in computational costs while maintaining high efficiency of the design solutions.

Keywords: morphing wing, high-lift devices, airfoil optimization, unmanned aviation vehicle.

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Оптимизация профиля адаптивного крыла малоразмерного беспилотного воздушного судна

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Аннотация: Современные малоразмерные беспилотные воздушные суда (БВС) выполняют широкий спектр задач, что требует от них высокой эффективности в различных, часто противоречивых, режимах полета. Аэродинамические профили, оптимизированные под один конкретный режим, демонстрируют неоптимальные характеристики в других, что ограничивает общие летные возможности судна. Перспективным решением данной проблемы является использование адаптивного крыла, способного изменять свою форму в полете. В данной работе представлен метод упрощенной многокритериальной оптимизации профиля такого адаптивного крыла. Для преодоления вычислительной сложности классического подхода с построением фронта Парето, особенно при большом количестве режимов полета, многокритериальная задача была сведена к однокритериальной форме. Это достигнуто с помощью метода взвешенной суммы целевых функций, которые были нормализованы по эталонным (идеальным) значениям коэффициента лобового сопротивления. Расчет весовых коэффициентов осуществлен на основе физического параметра – числа Рейнольдса, что

позволяет сфокусировать оптимизационный алгоритм AeroSandBox на наиболее важном, крейсерском режиме. Геометрия профиля параметризована методом класса-формы (CST), а для быстрых и точных аэродинамических расчетов использовался инструмент NeuralFoil на основе физически информированного машинного обучения. В работе решены две оптимизационные задачи: для двух и четырех режимов полета. Результаты двухточечной оптимизации качественно и количественно согласуются с данными, полученными независимо более сложными методами. Показано, что использование идеализированного механизма адаптации кривизны обеспечивает достижение компромиссным профилем 82,7–87,5% от аэродинамического качества эталонных профилей, оптимизированных для каждого режима в отдельности. Предложенный метод демонстрирует снижение вычислительных затрат при сохранении высокой эффективности проектных решений.

Ключевые слова: адаптивное крыло, механизация крыла, оптимизация профиля крыла, беспилотное воздушное судно.

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Introduction

Modern small unmanned aerial vehicles (UAVs) are tasked with a wide range of missions, necessitating operation across various and often conflicting flight conditions. This imposes contradictory demands on the aerodynamic performance of the wing, as an airfoil optimized for one specific flight condition typically exhibits suboptimal performance in another. The use of a morphing wing, capable of dynamically altering its shape in flight, presents a potential solution to this challenge [1].

Morphing wings can be broadly classified based on the specific parameters they alter during flight. A particular category of interest is the variable-camber morphing wing [2, 3]. Smooth camber variation not only allows the airfoil parameters to be adapted to current flight conditions but can also enhance the lift properties of the wing compared to conventional simple flaps, leading to reductions in takeoff and landing distances [4]. Furthermore, in comparison to slotted flaps, morphing flaps have the potential to reduce wing structural weight and mitigate unsteady loads on high-lift devices due to flow separation [5].

Compliant mechanisms, based on elastic material deformation, are of particular interest for small UAVs [6]. Lacking traditional rigid links and hinge joints, these structures offer potential advantages in reliability and maintainability, making them suitable for morphing wing applications [7]. For instance, the surfaces of an airfoil can be defined by an open contour, and the

displacement of one end leads to a change in the camber of the trailing edge [8, 9].

Research in the field of morphing wings often focuses on analyzing the effects of varying parameters on a *given* airfoil [10, 11]. A fundamentally different approach was proposed in [12], where the constraints of a real camber morphing mechanism (FishBAC) were integrated directly into a two-level multi-objective optimization process involving a Pareto front. While scientifically rigorous, this approach becomes impractical for problems with numerous objectives ($N > 3$) due to exponential growth in computational cost (increasing both population size and the proportion of non-dominated solutions) [13] and the complexity of visualizing the results [14].

The objective of this study is to develop and verify a simplified method for the multi-objective optimization of an airfoil for a small UAV's morphing wing. This method is based on the scalarization of objective functions using weighting coefficients and normalization by reference values. Additionally, the effectiveness of an idealized variable-camber wing mechanism across different UAV flight regimes is examined.

Materials and Methods

Airfoil optimization for n flight conditions constitutes a multi-objective problem, formulated as finding a design variable vector X that minimizes a set of objective functions:

$$\min \{f_1(X), f_2(X), \dots, f_i(X)\}, \quad (1)$$

where f is the objective function, typically expressed as the drag coefficient for the i -th flight condition under specified targets and constraints.

This problem can be addressed using methods that construct an n -dimensional Pareto front. However, as noted in the introduction, the computational complexity of this approach becomes prohibitively high for a larger number of flight condition $N > 3$, especially when considering nested optimization over the angle of attack and camber values. This is due to the exponential growth in the required population size for genetic algorithms and the increase in the proportion of non-dominated solutions [13].

To reduce computational complexity, the multi-objective problem can be converted into a single-objective form using scalarization techniques. The weighted sum method, one of the simplest approaches [15], with normalization of the objective functions, defines an aggregated objective function $F(X)$ as:

$$\min F(X) = \sum_{i=1}^n (w_i \cdot \frac{f_i(X)}{f_i^*}), \quad (2)$$

where $f_i(X)$ is the value of the i -th objective function (in the current study, C_{d_i});

f_i^* is the reference (normalizing) value for i -th objective function;

w_i is the weight for the i -th objective function, with $\sum w_i = 1$.

The reference values f_i^* were obtained by solving n independent single-objective optimization problems for each i -th flight condition:

$$\text{Minimize: } f_i(X) = C_{d_i}^{ref} \quad (3)$$

$$\text{Subject to: } C_{l_i}^{obj}, \text{ Re}_i, M_i$$

Varying: (X) = (airfoil geometry parameters, angle of attack α).

Thus, $f_i^* = C_{d_i}^{ref}$ is the minimum achievable drag value for the i -th flight condition, obtained for a reference airfoil specific to that condition. Normalizing $f_i(X)$ by f_i^* mitigates the issue of dominance by objective functions with larger absolute values (i.e., takeoff and landing).

The selection of weights w_i represents a critical step that inherently involves some subjectivity [16]. In this study, for cases with $N > 2$ criteria, the weights were calculated using a method based on a physical parameter characterizing the flight regime (Reynolds number) and by identifying a control (most important) k -th condition, which was selected as the cruise flight mode.

For each j -th flight condition, a value d_j is calculated, characterizing its “proximity” to the control k -th condition based on parameter P (in this case, $P = \text{Re}$):

$$d_j = 1 - \frac{|P_j - P_k|}{P_{\max}}, \quad (4)$$

where P_j is the parameter value (Re) for the j -th flight condition;

P_k is the parameter value for the control k -th condition;

$P_{\max}$ is the maximum value of parameter P among all n criteria.

Then, d_j values were normalized by their sum to satisfy the $\sum w_i = 1$ condition:

$$w_j = \frac{d_j}{\sum_{i=1}^n d_i}. \quad (5)$$

The airfoil geometry was parameterized using the Class-Shape Transformation (CST) method [17]. This approach provides a smooth and flexible definition of the airfoil contour using 18 variables. The symmetric NACA 0012 airfoil was selected as the baseline for initialization. For aerodynamic calculations, the NeuralFoil soft-

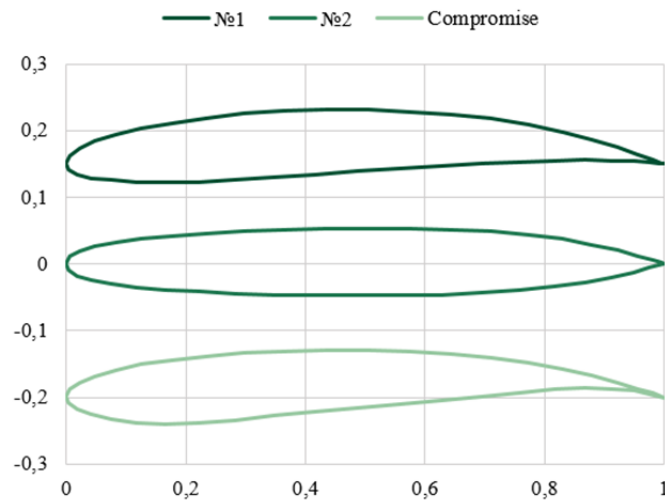


Fig. 1. Airfoils obtained from two-point optimization problem

ware [18] was employed. This tool utilizes physics-informed machine learning, offering significantly reduced computational time compared even to conventional panel methods. The optimization was performed within the AeroSandbox environment [19], which provides gradient-based optimization methods with automatic differentiation.

The following geometric constraints were imposed on the airfoil parameters for all calculated configurations: minimum relative thickness $\overline{t_{\min}} > 0\%$, maximum relative thickness $\overline{t_{\max}} = 10\%$, and a leading-edge radius $\overline{r_{LE}} \geq 1\%$ of the chord length c . A simplified kinematic model based on [20] was used to simulate the camber variation of the morphing wing. This model assumes a smooth rotation of points in the airfoil's trailing-edge section by a uniformly increasing angle δ .

Results

Two-objective optimization

To initially validate the simplified method, an airfoil optimization was performed for two UAV flight conditions described in [12]. This allows for an indirect comparison, demonstrating that the proposed approach yields results of the same order of magnitude as more complex methods.

The optimization was conducted in three stages:

1. For condition № 1 («Loiter»): minimize C_{d_1} subject to $C_{l_1}^{obj} = 0.8$, $Re_1 = 6.5 \cdot 10^5$, $M_1 = 0.1$, resulting in a reference airfoil with $C_{d_1}^{ref} = 0.00565$.

2. For condition № 2 («Dash»): minimize C_{d_2} subject to $C_{l_2}^{obj} = 0.046$, $Re_2 = 2.5 \cdot 10^6$, $M_2 = 0.417$, resulting in a reference airfoil with $C_{d_2}^{ref} = 0.00300$.

3. For the compromise airfoil: minimize $F(X) = \frac{C_{d_1}}{C_{d_1}^{ref}} + \frac{C_{d_2}}{C_{d_2}^{ref}}$ with constraints for both conditions and equal weights.

The optimized profiles are shown in Figure 1. Analysis of drag coefficients (tab. 1) shows that the compromise airfoil exhibits a 6.46% performance penalty relative to the Loiter condition and 41.41% relative to the Dash condition.

It is important to note that despite differences in computational tools and optimization algorithms, the overall nature and order of magnitude of the results align with the data from the referenced publication, which reported performance losses of 3.72% and 40.81%, respectively.

Table 1
Comparison of airfoils C_d

Condition	C_d^{ref}	C_d^{comp}	C_d^{ref} / C_d^{comp} , %
Results from [12]			
№ 1	0.00544	0.00565	3.72
№ 2	0.00335	0.00566	40.81
Present Study			
№ 1	0.00565	0.00604	6.46
№ 2	0.003	0.00512	41.41

Four-objective optimization

The primary objective of this study was the optimization of an airfoil for four flight conditions typical of a small UAV (tab. 2). The weights for the aggregate objective function were calculated based on the proximity of the Reynolds number of each i -th flight condition to the control k -th cruise flight condition (№ 3).

Table 2
Flight conditions in four-objective optimization problem

Condition	C_l^{obj}	$Re, (\cdot 10^5)$	M	w
№ 1	1.41	4.0	0	0.1875
№ 2	0.65	6.0		0.25
№ 3	0.35	8.0		0.3125
№ 4	0.22	10.0		0.25

Reference airfoils for each condition were obtained by solving four independent single-objective optimization problems of the form (3). A single compromise airfoil was obtained by solving single four-objective problem considering the weights from Table 2 and normalizing C_{d_i} by the values $C_{d_i}^{ref}$ of the reference airfoils according to equation (2). To adapt this compromise airfoil to each flight condition using a hypothetical device (with hinge at 70% chord), nested optimization tasks were solved to find the optimal camber deflection angles δ for minimizing C_d in each condition. The optimal deflection angles δ for conditions № 1–4 were -5.0° , -3.0° , 0° , and $+2.0^\circ$, respectively.

Figure 2 illustrates the shapes of the resulting airfoils – the compromise one obtained with and without objective function normalization, while Figure 3 presents the set of reference airfoils alongside the optimal variations of the compromise airfoil achieved through the morphing mechanism.

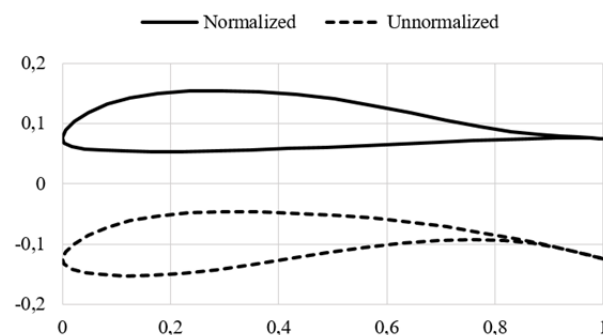


Fig. 2. Normalized and unnormalized compromise airfoil

Figure 4 presents the ratio of $K = C_l / C_d$ value of the morphed compromise airfoil variations to the $K_{opt} = C_l^{opt} / C_d^{opt}$ value of the reference airfoils for each flight condition. When using a static compromise airfoil (without the morphing mechanism), this ratio drops to 50.1%. Employing the camber adaptation mechanism with optimal deflection angles δ increased this ratio to a range of 82.7–87.5% across the different flight regimes.

Figure 5 demonstrates the stability and adequacy of the aerodynamic performance for the variations of the compromise airfoil. The well-behaved polar curves indicate that the optimization algorithm did not exploit potential errors in the computational or parametric methods to find unrealistic minima.

Conclusion

This work has presented and verified a method for simplifying the multi-objective optimization of an airfoil for a morphing wing, based on the scalarization of criteria. The method reduces the computational complexity of design problems where multiple UAV flight conditions must be considered.

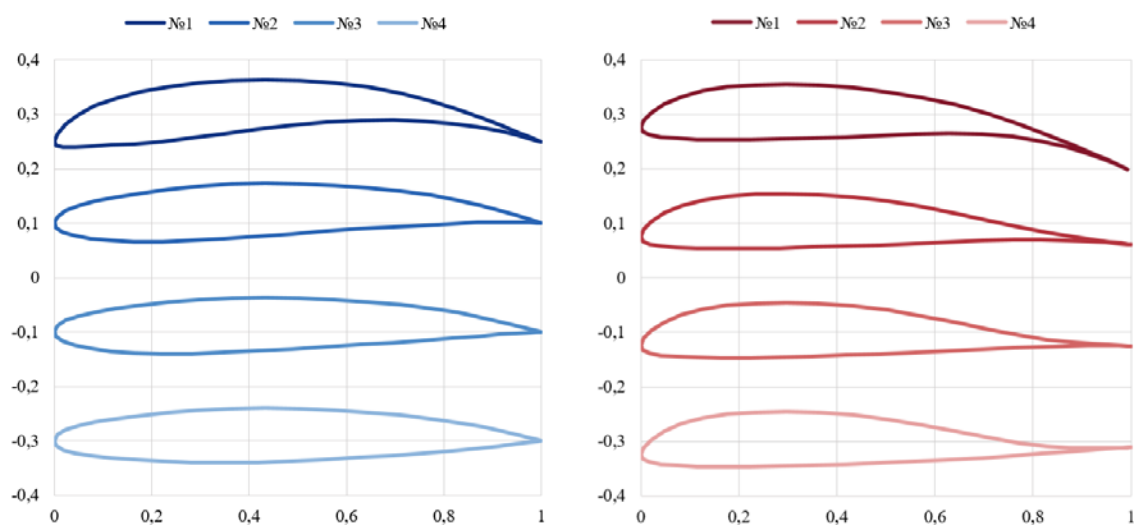


Fig. 3. Reference airfoils (left) and optimal variations of compromise airfoil provided by morphing mechanism (right)

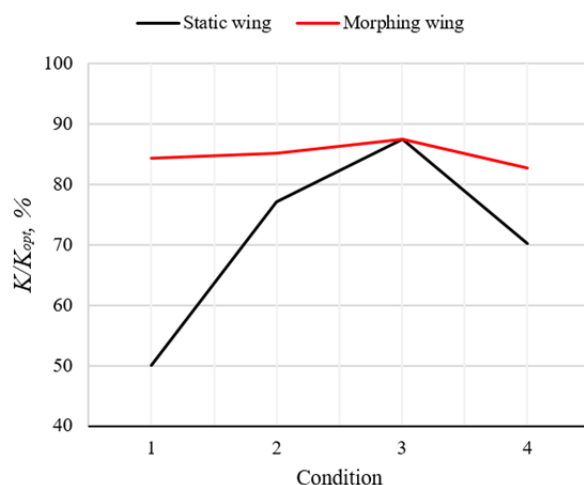


Fig. 4. Current $K = C_l / C_d$ to optimal $K_{opt} = C_l^{opt} / C_d^{opt}$ ratio for static compromise airfoil and morphing wing

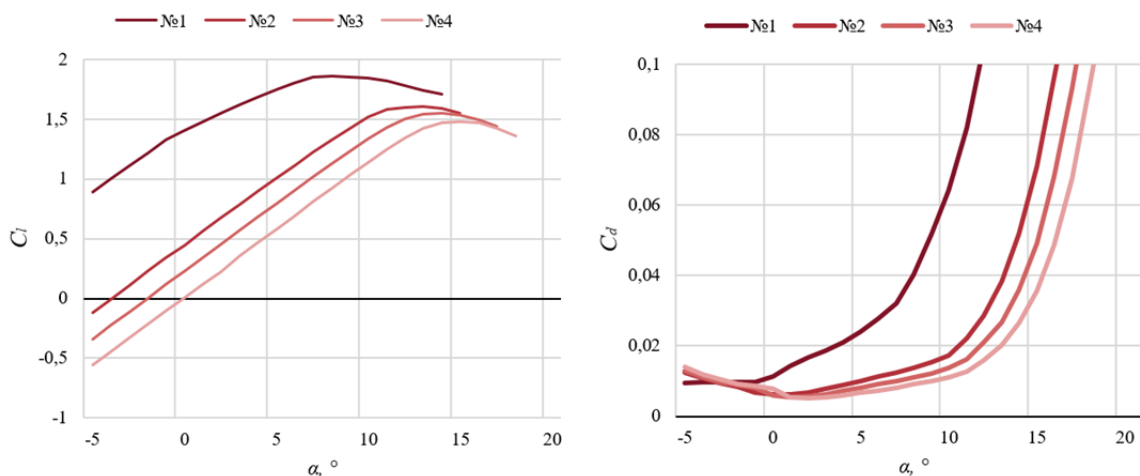


Fig. 5. Aerodynamic performance of variations of compromise airfoils

The principal findings are as follows:

1. The weighted sum method, incorporating weights assigned based on the physical parameters of the flight regime (Reynolds number) and normalization of the objective functions relative to their reference (ideal) values, successfully eliminated the dominance of objectives with large absolute values and allowed focus on the most important control flight regime.

2. Verification of the method using a two-objective optimization problem demonstrated that, despite a radical simplification of the problem and the use of different computational tools, the proposed approach yielded results that were in good qualitative and quantitative agreement with data independently obtained by more complex methods.

3. A four-objective airfoil optimization, which integrated an idealized mechanism kinematics, achieved performance close to that of the reference (ideal) airfoils when different camber deflection angles δ were applied.

Discussion

Reducing the multi-objective problem to a single-objective formulation significantly decreased computational costs while maintaining the compromise airfoil's effectiveness, achieving 82.7–87.5% of the efficiency of the reference cases. The largest performance deficit was observed for the flight condition, which had the smallest weight $w_1 = 0.1875$. Key limitations of the adopted approach include the lack of explicit information on potential trade-offs between objectives and the inherent degree of subjectivity involved in selecting the control condition k and the parameter P for calculating the weights.

As mentioned earlier, morphing wing research often involves analyzing the effects of shape change on a given airfoil. For instance, the study in [11] defined part of the mean camber line of a symmetric airfoil using a third-order curve while varying the position of a hypothetical hinge (at 25%, 50%, and 75% chord). Reference [20] compared a simple plain flap with a morphing flap, demonstrating the aerodynamic

advantages of the latter, partly due to delayed boundary layer separation.

A fundamentally different approach is exemplified by [12], which employed a two-level, multi-objective optimization with Pareto front construction. The method used in the present study cannot fully replace such an approach, particularly in problems where a complete picture of all possible trade-offs is essential. However, the method is well-suited when seeking a single high-quality solution with minimal computational resources. Other strategies for reducing computational cost include clustering flight conditions or optimal solutions [21], employing particle swarm optimization [22], or utilizing other scalarization techniques.

Future research directions include: 1) Refining methods for assigning weights – for instance, based on the relative mean dwell time or fuel consumption in a flight regime; 2) Integrating structural (topology) optimization algorithms for compliant mechanisms directly into the airfoil search process (an example is shown in [23]); 3) Extending the method to three-dimensional conditions while accounting for associated aerodynamic losses.

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