Quy Trình Thiết Kế Tối Ưu Cho Biên Dạng Cánh Vận Tốc Thấp Sử dụng Phân tích Đa Độ Tin Cậy Cho Thiết Bị Bay Không Người Lái Dạng Cánh Bay

An Efficient Low-Speed Airfoil Design Optimization Process Using Multi-Fidelity Analysis for UAV Flying Wing

Anh Bao DINH[1], Khanh Hieu NGO[2], Nhu Van NGUYEN[3]
HCM City University of Technology, Vietnam.
e-Mail: dinhanhbao1991@gmail.com, ngokhanhhieu@hcmut.edu.vn, nhuvanvn@konkuk.ac.kr

Abstract:
This paper proposes an efficient low-speed airfoil selection and design optimization process using multi-fidelity analysis for a long endurance Unmanned Aerial Vehicle (UAV) flying wing. The developed process includes the low-speed airfoil database construction, airfoil selection and design optimization steps based on the given design requirements. The multi-fidelity analysis solvers including the panel method and computational fluid dynamics (CFD) are presented to analyze the low speed airfoil aerodynamic characteristics accurately and perform inverse airfoil design optimization effectively without any noticeable turnaround time in the early aircraft design stage. The unconventional flying wing UAV design problem issues are poor in longitudinal stability but low parasite drag resulting in the long endurance and better performance. The multi-fidelity analysis solvers are validated for the E387 airfoil compared to the wind tunnel test data. Then, 29 low speed airfoils for flying wing UAV are constructed by using the multi-fidelity solvers. The weighting score method is used to select the appropriate airfoil for the given design requirements. The selected airfoil is used as a baseline for the inverse airfoil design optimization step to refine and obtain the optimal airfoil configuration. The implementation of proposed method is applied for the real flying-wing UAV airfoil design case to demonstrate the effectiveness and feasibility of the proposed method.

Keywords: Low-speed airfoil, Airfoil design optimization, multi-fidelity analysis, CFD, Flying wing UAV

Nomenclature

Symbol	Unit	Definition
C_{lo}		2D airfoil lift coefficient
C_{mo}		2D airfoil pitching moment coefficient
$C_{l\max}$		Maximum lift coefficient
a_{stall}	deg	Stall angle of attack, in degrees
$C_{d\min}$		Minimum drag coefficient
C_l / C_d		Lift-drag ratio
y/c	% chord	Location of airfoil point along the y-axis
x/c	% chord	Location of airfoil point along the x-axis
r	kg/m^3	Density
v	m/s	Airspeed
c	m	Chord
m	kg/m.s	Dynamic viscosity
Re		Reynolds number
U_i	m/s	Instantaneous velocity
u_i'	m/s	Fluctuating velocity
m_t	kg/m.s	Eddy viscosity
k		Turbulent kinetic energy
d_{ij}		Kronecker number

1. Introduction

Airfoil plays an extremely important role for the aircraft aerodynamics, performance and stability. Therefore, the airfoil selection process is very essential and significant at the early aircraft design stage to support designers for selecting an appropriate airfoil with the given requirements. The basic airfoil aerodynamic characteristics include airfoil lift, drag, and pitching moment coefficient that are required to evaluate by performing the test at the specific working condition of the airfoil. For example, many airfoil aerodynamics data were tested at the 2.8×4.0 *ft* (0.853×1.219 m) low-turbulence wind tunnel in the Subsonic Aerodynamics Research Laboratory at the University of Illinois at Urbana-Champaign (UIUC) [1]. However, doing such a test could be time-consuming and costly. Moreover, errors could be

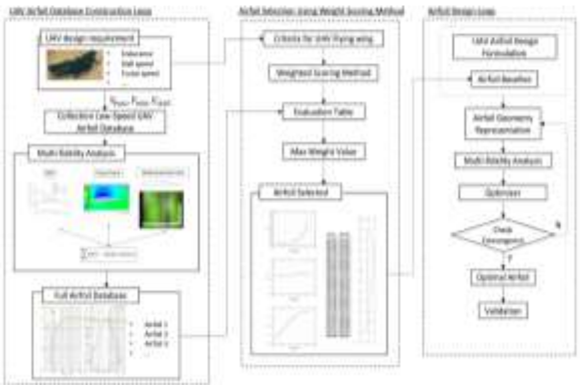
[1] Undergrad, Department of Aeronautical Engineering, HCM City University of Technology, Vietnam.
[2] Lecturer, Department of Aeronautical Engineering, HCM City University of Technology, Vietnam
[3] Assistant Professor, Department of Aerospace Information Engineering, Konkuk University, South Korea.

made because the working condition of the selected airfoils is not always the same as the testing data as the result of approximation [1]. Hence, many researchers currently implement the reliable and accurate prediction analysis tools such as panel method, Reynolds-averaged Navier-Stokes (RANS), and in-house CFD solvers to analyze and design airfoil. However, the different analysis methods are required for the different flow conditions. In this paper, the flight regime is the low-speed which means the flow through the airfoil includes three regions: laminar, turbulent and transition zone. Besides, the high-fidelity analysis has fully turbulent problem. Thus, the drag coefficient estimation is over-predicted that compared to the experiment results at the low speed regime. Meanwhile, the low-fidelity analysis estimates less accurately for terms of the lift but pretty good about drag problem [2]. *P. D. Silisteanu et al.* introduced a method for estimating the transition onset and extent based on the temporal parameter of the skin friction coefficient and flow vorticity at the wall [2]. This method shown that the relative error in the drag coefficient calculated is lower than 8%, when a fully turbulent can introduce error up to 50%. *R.B. Langtry et al.* used the $g - \overline{\mathrm{Re}_{qt}}$ model for low-speed [3]. This model requires the solution based on two transport equation, one for intermittency and one for a transition onset criterion in terms of momentum thickness Reynolds number. Since its development, the $g - \overline{\mathrm{Re}_{qt}}$ model has been adapted by *A. C. Aranake et al.* [4] for use with the Spalart-Allmaras turbulent model [5] and $k - w$ turbulent model [6]. The Spalart-Allmaras model is more widely used application for aerospace applications involving wall-bounded flows, and it is also typically less expensive, one transition equation. However, in order to perform these methods, the knowledge of Computer Fluid Dynamics (CFD) is required. The panel method is XFLR5 code [18]. *Mark Drela* [7] used an inverse method incorporated in Xfoil based on surface speed distribution of airfoil baseline. There are two types of this method: full inverse and mixed inverse. It calculates the entire airfoil. Similarly, *T. R. Barrett et al.* [8] used the inverse method by RANS solver as a high-fidelity analysis. However, these methods have difficulties for modifying the surface speed distribution. Hence, some methods are developed to airfoil shape parameterization. One of the most popular method for airfoil representation is the Bézier curve, which introduces control point around the geometry. These points are used to define the airfoil shape. *N. V. Nguyen et al.* [9] modeled airfoil geometry by the class shape function transformations (CST) method [10]. CST method is defined by combined class function with shape function. *Ma Dongli et al.* [11], *Ava Shahrokhi et al.* [12] and *Slawomir Koziela et al.* [13] used airfoil NACA function instead of airfoil basline.

Besides, the limited slope of my design is to the MUAV operation speed of 20 m/s, the Mach number is 0.06. Therefore, this paper proposed the efficient airfoil selection and design optimization process that uses the multi-fidelity including panel method and CFD solvers. The flying wing UAV is well-known for high performance due to the low parasite drag with the same engine power.

2. Efficient low-speed airfoil design optimization process

The overall process of efficient low-speed airfoil design optimization is presented in F. 1. It includes three-steps that are UAV airfoil database construction loop, airfoil section loop and airfoil design optimization loop. The framework starts with UAV airfoil database construction loop. The fully airfoil database is generated based on requirements and executed by the multi-fidelity analysis, used to send airfoil section loop. In the airfoil section loop, from the fully airfoil database, Weighted Scoring Method (WSM) is employed for finding maximum weight value by criteria for the UAV flying wing. Then, airfoil selected is sent airfoil design optimization loop. In here, airfoil selected is used to airfoil baseline for design optimal airfoil.



F. 1 *Efficient Low-Speed Airfoil Design Optimization*

2.1 UAV airfoil database construction loop

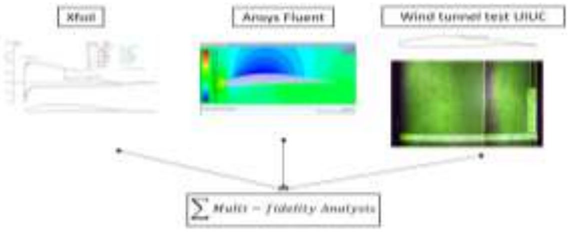
The design of an aircraft or UAV generally begins with identifying requirements, i.e. endurance, stall speed, cruise speed in UAV airfoil database construction loop. Then, finding suitable Airfoils by using requirements. Airfoils in the collection are sent to the multi-fidelity analysis, in which panel method and RANS method, to obtain results of aerodynamic i.e. maximum lift coefficient, angle of attack, and drag coefficient. Then, the results are collected in a fully airfoil database.

In this loop, the most important step is Multi-Fidelity Analysis (see F. 2). The multi-fidelity analysis includes the panel method and Reynolds-averaged Navier-Stokes (RANS) solver by XFOIL and ANSYS FLUENT.

XFOIL

XFOIL [7] is probably the best known of the above codes. It dates back to 1986 and was written by Dr. Mark Drela, an aerodynamics professor at the

Massachusetts Institute of Technology. It is coupled panel method with an integral boundary layer calculation for analysis (see F. 3). When the angle of attack is specified, it uses a general inviscid airfoil flow field, constructed by the superposition of a free stream flow, a vortex sheet of strength, γ , on the airfoil surface, and source sheet strength, σ , on the airfoil surface and wake. The airfoils contour and wake trajectory are discretized into flat panels, with panel nodes on the airfoil and wake. The influence of viscous effects so a new source influence matrix would have to be calculated each time the wake trajectory is changed. Iteration between source influence matrix and e^N -envelope method [14], to calculate transition, solutions is continued until a suitable convergence on the boundary-layer displacement thickness is achieved.



F. 2 *Multi-fidelity analysis*

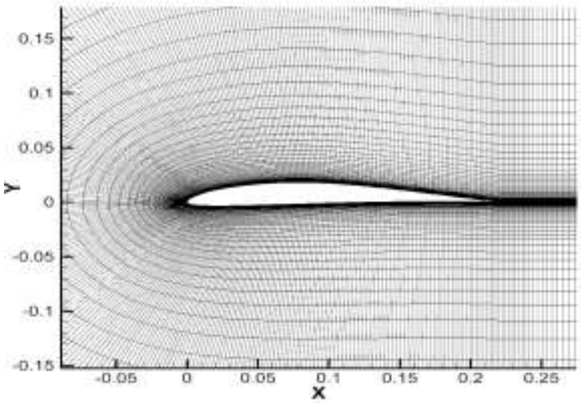
F. 3 *Panel nodes on the airfoil and wake [7]*

ANSYS FLUENT 13

FLUENT [17] is a Navier-Stokes solver that can operate in either two-dimensional or three-dimensional models, solvers are based on the finite volume method (FVM). Besides, CFD needs fine grid generation, and the structured grid (see F. 4) is more preferable than unstructured grid since it can avoid the divergence caused by rough grid. The user is allowed a wide selection of turbulence models. In this paper, low Reynolds number flow mechanism is expounded by the numerical simulation of several airfoils using Reynolds-averaged Navier-Stokes (RANS) equations. The solution schemes were steady time and pressure-based.

The RANS equations and the continuity equation without the gravity and the body force item in Cartesian tensor form:

$$\begin{cases} \dfrac{\partial U_i}{\partial x_k} = 0 \\ \rho\left(\dfrac{\partial U_i}{\partial t} + U_k \dfrac{\partial U_i}{\partial x_k}\right) = -\dfrac{\partial p}{\partial x_i} + \dfrac{\partial p}{\partial x_j}\left(\mu \dfrac{\partial U_i}{\partial x_j}\right) \\ \qquad + \dfrac{\partial\left(-\rho\overline{u_i u_j}\right)}{\partial x_j} \end{cases} \tag{1}$$



F. 4 *Structured grid*

The term $-\rho\overline{u_i u_j}$ is a time-average rate of momentum transfer due to the turbulence. It describes the complexity of turbulent flow and is the cause of the closure problem (defined below). The specific Reynolds stress tensor is defined as:

$$R_{ij} = -\rho\overline{u_i u_j}, R_{ij} = R_{ji} \tag{2}$$

The stresses that arise from this term are known as Reynolds-stresses, and they add six more unknowns to the system. With three of the velocity components and one of the pressure, the total number of unknowns for turbulent flow is now ten. Since the number of equations is still only four, the system is not closed. This is referred to as the closure problem.

In 1877, The Boussinesq eddy-viscosity approximation is Reynolds stresses might be proportional to mean rates of deformation. Eddy viscosity, μ_t , and the turbulent kinetic energy, k , are solved by transport equations.

$$R_{ij} = -\rho\overline{u_i u_j} = \mu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \frac{2}{3}\rho k \delta_{ij} \tag{3}$$

Table 1. *Turbulent models*

Turbulent model	Number of equation
Spalart-Allmaras	One-Equation
Standard $k-\omega$	Two-Equation
RNG $k-\omega$	
Realizable $k-\omega$	
Standard $k-\varepsilon$	Two-Equation
SST $k-\omega$	

2.2 Airfoil section loop

Identify criteria for UAV flying wing by using requirement of Airfoil Database Loop. Weighted Scoring Method (WSM) is employed for finding maximum weight value from the Fully Airfoil Database. The airfoil has maximum score is found.

Criteria for UAV Flying wing

From UAV design requirement, the criteria for the best performance have to be set in order to select the proper airfoil. The criteria for each parameter are shown in the Table 1 as follows.

Table 2. *Criteria for flying wing airfoil selection*

No.	Coefficient	Criteria	%
1	C_{lo}	Close to $C_{lcruise}$ is the best	$A_1\%$
2	C_{mo} at 0 deg	Low magnitude is best	$A_2\%$
3	C_{mo} at 2 deg	Low magnitude is best	$A_3\%$
4	$C_{l\max}$	Highest is the best	$A_4\%$
5	α_{stall}	Highest is the best	$A_5\%$
6	$C_{d\min}$	Lowest is the best	$A_6\%$
7	C_l / C_d $C_{d\min}$ max	Highest is the best	$A_7\%$
8	$C_l^{1.5} / C_d$ max	Highest is the best	$A_8\%$

Weight Scoring Method

Weighted Scoring Method (WSM) is a selection method comparing multi criteria. It includes determining all the criteria related to the selection, giving each criteria a weighted score to reflect their relative importance and evaluation of each criteria.
WSM consists of these following steps:

- Determining all the criteria as shown in Table 2.
- Creating evaluation table for each airfoil is based on criteria, as shown in Table 3.
- Making sum of all the products and selecting the airfoil with the highest total points from the full airfoil database.

Table 3. *Evaluation table*

Airfoil	Criteria	Airfoil 1	Airfoil 2	…	Airfoil n
C_{lo}	$A_1\%$	1_1	2_1	…	n_1
C_{mo} at 0 deg	$A_2\%$	1_2	2_2	…	n_2
C_{mo} at 2 deg	$A_3\%$	1_3	2_3	…	n_3
$C_{l\max}$	$A_4\%$	1_4	2_4	…	n_4
α_{stall}	$A_5\%$	1_5	2_5	…	n_5
$C_{d\min}$	$A_6\%$	1_6	2_6	…	n_6
C_l / C_d max	$A_7\%$	1_7	2_7	…	n_7
$C_l^{1.5} / C_d$ max	$A_8\%$	1_8	2_8	…	n_8
Total	100%	$\sum_i^8 1_i A_i$	$\sum_i^8 2_i A_i$	…	$\sum_i^8 n_i A_i$

2.3 Airfoil design optimization loop

Design formulation

Flying wing configuration operates at high speed with the low parasite drag, but stability issues inherent in this type of configuration. Thus, the improvement of pitching coefficient in cruise conditions is selected as an objective function for the current UAV airfoil design. The aerodynamic constraints are maximum lift coefficient, stall angle of attack, minimum drag coefficient and the coordinates of airfoil selected are used as design variables.
The 2D airfoil design problem can be written as a standard optimization problem:

$$\text{Maximize}: \mathrm{f}(\bar{\mathrm{x}}) = C_{mo} \tag{4}$$

Subject

$$\begin{cases} C_{l\max} \geq C_{l\max\_selected} \\ \alpha_{stall} \geq \alpha_{stall\_selected} \\ C_{d\min} \leq C_{d\min\_selected} \end{cases} \tag{5}$$

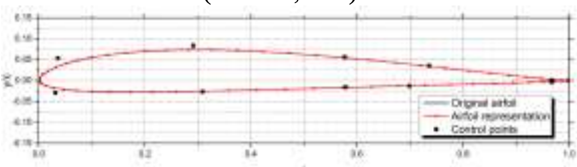
Airfoil geometry representation

Airfoil geometry is modeled as a projective Bézier curve. The general form of the mathematical expression is:

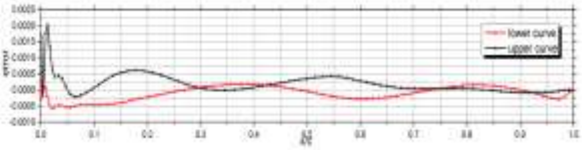
$$B(u) = \sum_{i=0}^{n} a_i b_{i,n}(u), where: B(u) = \frac{y}{c}, u = \frac{x}{c} \tag{6}$$

$$b_{i,n}(u) = \binom{n}{i} u^i (1-u)^{n-i}, where \binom{n}{i} = \frac{n!}{i!(n-i)!} \tag{7}$$

As see that the Bézier curve is a weighted sum of the control points, a_i. By changed "control point" of Bézier curve of airfoil selected baseline, I have new airfoil coordinates (see F. 5, F. 6).



F. 5 *Airfoil representation*



F. 6 *Error upper and lower curve*

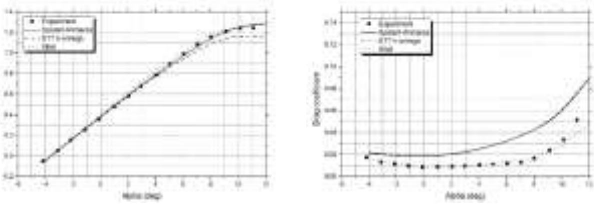
Optimizer

Airfoil geometry representation is sent to multi-fidelity analysis. If the convergence is not satisfied, airfoil geometry representation will be updated by change control point.

3. Multi-fidelity analysis solver validation

The E387 airfoil was designed by Richard Eppler in the mid-1960s for use in model sailplanes. Because it was designed specifically for the appropriate lift coefficients and Reynolds numbers required by its application, this airfoil became a touchstone for much of the research directed at increasing the understanding of low Reynolds number airfoil aerodynamics.

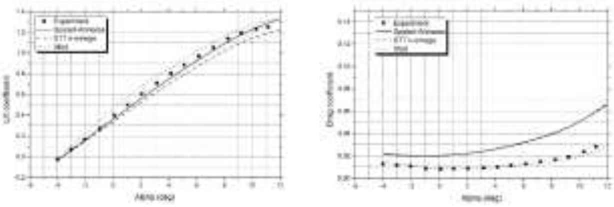
The aerodynamic characteristics predicted for Re = 300000 by XFOIL and FLUENT are compared to the UIUC wind-tunnel measurements [15]. A C-type grid with 33450 nodes, 33004 cells, 66454 faces and $y_{wall}+$ = 1.0 is generated for the ANSYS FLUENT using the Pointwise tool [16].



a) Lift coefficient *b) Drag coefficient*

F. 7 *Comparison of predicted and measured aerodynamic characteristics for the E 387 airfoil, Re = 300000.*

In F. 7, these results are compared with those from the UIUC wind-tunnel for Re 300000. As seen from F. 7.a, these analytical tools have high-fidelity, STT k-omega turbulence model is lower results of wind tunnel test, and Xfoil is upper. Besides, Spalart-Allmaras turbulence models matched with experiment. This case study is the low Mach number, exist both laminar and turbulent flow. In the FLUENT tool, the turbulence models used in the fully turbulent so drag coefficient is higher XFOIL, uses a semi-empirical equation boundary layer and transition. Besides, results of multi-fidelity analysis of CAL2463m airfoil is same, as shown in F. 8. So, Spalart-Allmaras turbulence model is used for lift coefficient and XFOIL for the drag coefficient.



a) Lift coefficient *b) Drag coefficient*

F. 8 *Comparison of predicted and measured aerodynamic characteristics for the CAL2463m airfoil, Re = 300000.*

4. Case study: UAV flying wing airfoil design optimization

4.1 UAV Airfoil Database Construction Loop

Table 4. *UAV design requirement*

	Value	Unit
Wing span	1.4	m/s
Fuselage length	0.6	m/s
Cruise speed	20	m/s
Operation all	100	m
Wing mean chord	0.22	m

From Table 4, we have Reynolds number for case study.

$$Re = \frac{\rho v c}{\mu} = \frac{1.225\times 20\times 0.22}{1.8\times 10^{-5}} = 300000$$

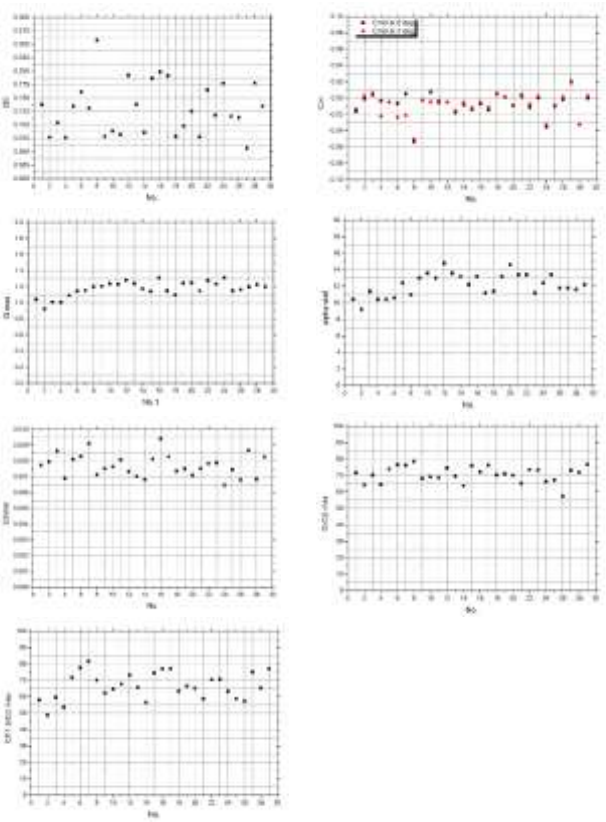
Then, Collection Low-speed UAV flying wing Airfoil database is searched, included 29 airfoils, using for selection, as shown in Table 5.

Table 5. *Collection Low-speed UAV flying wing Airfoil database*

No.	Airfoil	Thickness (%)	Camber (%)
1	E182	8.46	1.72
2	E184	8.32	1.20
3	E186	10.27	1.31
4	EH 1.0/9.0	8.99	1.00
5	EH 2.0/10	10.08	2.00
6	EH 2.5/10	9.99	2.49
7	EH 3.0/12	11.98	3.00
8	MH 32	8.66	2.23
9	MH 45	9.84	1.64
10	MH 60	10.07	1.76
11	MH 60-12%	11.99	1.74
12	TL 54	9.99	2.41
13	TL 55	9.44	1.90
14	TL 56	8.96	1.39
15	HS 3.0/8.0B	7.99	3.00
16	HS 3.4/12B	11.99	3.40
17	HS 3.0/9.0B	8.99	3.00
18	HS 2.0/8.0	7.99	2.00
19	HS 520	8.82	2.13
20	HS 522	8.67	2.01
21	HS 130	9.65	1.68
22	S 5.0/1.0	9.82	2.20
23	S 5.0/2.0	8.40	2.62

24	SD 7003	8.50	1.46
25	SIPKILL 1.7/10B	9.92	1.70
26	JWL-065	7.96	1.69
27	EMX-07	9.89	2.53
28	RS 400A	8.99	1.64
29	PHÖNIX	8.19	2.78

Using combine XFOIL and ANSYS FLUENT, I have results aerodynamic of 29 airfoils, as shown in F. 9.



F. 9 *Full Airfoil Database*

4.2 UAV Airfoil Database Construction Loop

UAV flying wing is low parasite drag and poor stability, so criteria of stability is important, as shown in Table 6.

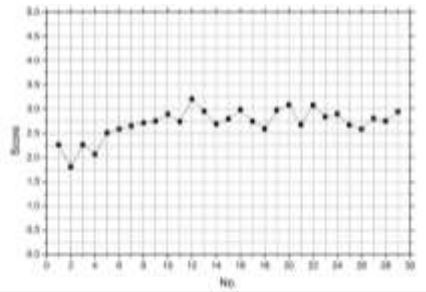
Table 6. *Criteria for case study*

No.	Coefficient	Criteria
1	C_{lo}	10%
2	C_{mo} at 0 deg	5%
3	C_{mo} at 2 deg	15%
4	$C_{l\,\max}$	20%
5	a_{stall}	15%
6	$C_{d\,\min}$	15%
7	C_l / C_d max	10%
8	$C_l^{1.5} / C_d$ max	10%

Decision for each criteria selection:

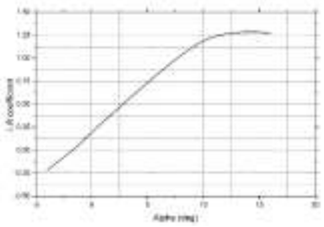
- C_{lo} : affecting the angle of incidence when take-off, 10%.
- C_{mo} at 0 deg and C_{mo} at 2 deg : important for stability, 5% and 15%.
- $C_{l\,\max}$: affecting the flight envelope of UAV, 20%.
- a_{stall} : important when flying at low speed, 15%.
- $C_{d\,\min}$: affecting for performance UAV, 15%.
- C_l / C_d and $C_l^{1.5} / C_d$: affecting for range and endurance, 10% for each coefficient.

Using WSM and Criteria in Table 6 for airfoil database, we have evaluation table to find airfoil have maximum weight value.

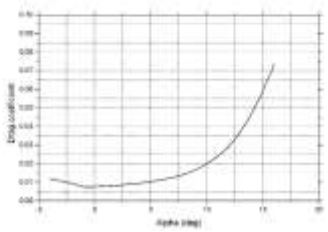


F. 10 *Score of Airfoil database*

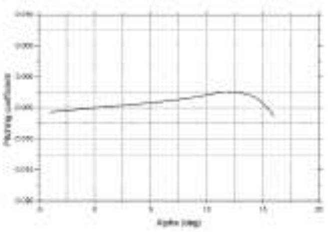
As shown in F. 10, the airfoil TL 54 (No.12) have maximum weight score, so airfoil baseline is TL 54.



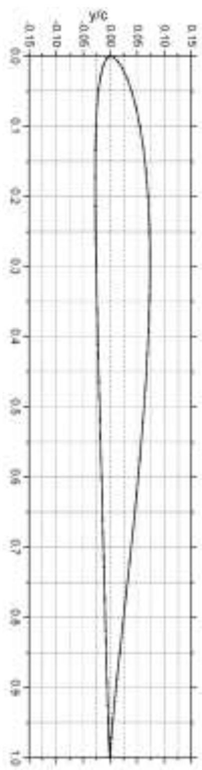
a) Lift coefficient



b) Drag coefficient



c) Pitch moment coefficient



c) Airfoil shape

F. 11 *Airfoil TL 54*

4.3 Airfoil Design Optimization Loop

As discussed above, the 2D airfoil design problem is based on TL54 (see F. 11) can be written as a standard optimization problem:

$$\text{Maximize}: f(\bar{x}) = C_{mo}$$

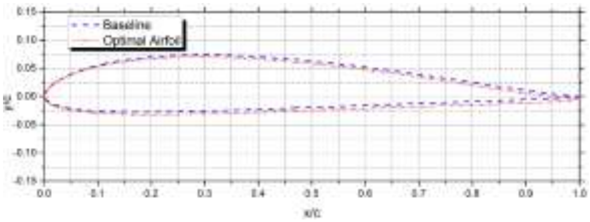
Subject to:

$$\begin{cases} C_{l\max} \geq C_{l\max\_TL54} \\ \alpha_{stall} \geq \alpha_{stall\_TL54} \\ C_{d\min} \leq C_{d\min\_TL54} \end{cases}$$

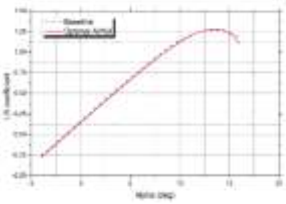
The optimal airfoil is shown in Table 7. The pitching moment coefficient of optimal airfoil increases 42.92% compared with the baseline airfoil TL 54. The maximum lift coefficient, stall angle of attack and minimum drag coefficient constraints are active.

Table 7. *Optimal Airfoil comparison*

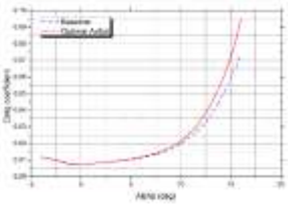
		Baseline (TL54)	Optimal airfoil	Unit
Objective	C_{mo}	-0.0049	-0.0028	-
Constraints	$C_{l\max}$	1.2702	1.278	-
	α_{stall}	14	14	deg
	$C_{d\min}$	0.0740	0.0736	-



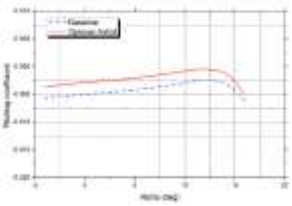
F. 12 *Baseline and optimal airfoil shapes*



a) Lift coefficient



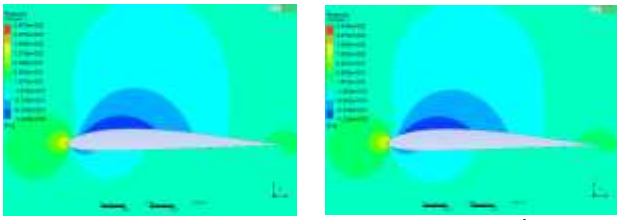
b) Drag coefficient



c) Pitch moment coefficient

F. 13 *Baseline and optimal airfoil polar comparison*

Small differences in the stall angle of attach, the maximum lift coefficient and the minimum drag coefficient, as shown in Table 7 and F. 13. For the pitching moment coefficient of optimal airfoil is so good, that increases stability of UAV flying wing. Besides, the pressure distribution of the airfoil for both optimal and baseline shows similar behavior F. 14.



a) Tl54 Airfoil *b) Optimal Airfoil*

F. 14 *Optimal airfoil pressure distribution at AOA = 0 deg*

5. Conclusion

An airfoil design optimization for airfoil TL54 is developed and applied successfully for improving the stability with a trustworthy optimum configuration providing a 42.92% improvement in reliability.

By using Multi-fidelity analysis for airfoil selection, designers don't have to spend time, for tested data on airfoils from the wind tunnel, still get results close to the experimental. Its accuracy and feasibility were demonstrated with the help of a case study. Thus, it is a promising approach for solving devices and time problems.

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Anh Bao DINH is a senior student from Department of Aerospace Engineering, Ho Chi Minh of Technology. As a student of P.F.I.E.V (Programme de Formation d'Ingénieurs d' Excellence au Vietnam) program, he has experienced in Small Unmanned Aerial Vehicle (SUAV) design, Computational Fluid Dynamic (CFD).

Dr. Khanh Hieu NGO received Bachelor degree in Aeronautical Engineering (2001) – Ho Chi Minh City University of Technology, M.S. degree in Mechanics (2002) and PhD. degree in Computer Science (2008) from ENSMA, France. Work experience: Control-Command Systems, Flight Mechanics, R&D, and Educator. Head of the Aerospace Engineering Lab., HCM City University of Technology.

Dr. Nhu Van NGUYEN graduated a Bachelor degree in Department of Aeronautical Engineering, Ho Chi Minh City University of Technology, February 2006. He earned a Doctor degree in Aerospace Engineering, Konkuk University, August 2011. The research areas are multidisciplinary aerospace vehicle design optimization, variable fidelity modeling, aircraft/UAV configuration design, surrogate models, and airworthiness. He has experienced in aerospace industry such as CS-VLA Subpart B aircraft design, MALE UAVs, and Micro UAVs design, fabrication and flight test. In addition, he has a strong publication record on the top Aerospace Engineering and Optimization Scientific Journals such as AIAA, Springer, Elsevier, Taylor & Francis, Royal Society Publisher. Currently, he is an Assistant Professor in Aerospace Information Eng., Konkuk University, South Korea.