



Design of a Small UAV Combined Between Flying-Wing and Quadrotor with XFRL5

Ngo Khanh Hieu, Pham Quang Vinh, Dinh Anh Bao

Department of Aerospace Engineering, Ho Chi Minh City University of Technology, Ho Chi Minh City, Vietnam

Email address:

ngokhanhhieu@hcmut.edu.vn (N. K. Hieu), quangvinhpham93@gmail.com (P. Q. Vinh), dinhanhbao1991@gmail.com (D. A. Bao)

To cite this article:

Ngo Khanh Hieu, Pham Quang Vinh, Dinh Anh Bao. Design of a Small UAV Combined Between Fixed-Wing and Quadrotor with Software XFRL5. *International Journal of Transportation Engineering and Technology*. Special Issue: Experiments Researches in Aeronautical Engineering. Vol. 2, No. 5-1, 2016, pp. 1-6. doi: 10.11648/j.ijtet.s.2016020501.11

Received: April 13, 2016; **Accepted:** July 22, 2016; **Published:** September 3, 2016

Abstract: The design process of a product is a multi-step process of selection and assessment criteria to create a final product which meets all the needs of the practice. A small UAV combined between flying-wing and quadrotor is a very complex product, so the design process of this small UAV requires a thorough and circumspect review. The problem is how to optimize the design and to carry out the testing of the feasibility of design requirements with the lowest cost and time savings. For that reason, many tools of Multi-Fidelity Analysis for UAV such as XFRL5, XFoil... have been used to give considerable support for this design process. This research focusses mainly on the analysis/design of the configuration of a small UAV flying wing based on the performance at its cruise speed.

Keywords: Small UAV Flying-wing, Quadrotor, XFRL5, Airfoil Selection for Small UAV

1. Introduction

Today, a quadcopter, also called a quadrotor helicopter or quad rotor has become popular as a type of unmanned aerial vehicle (UAV) with typical characters of maneuverability, stability, integration of applications for surveillance, film maker, photography, or toys... However, the downside of this configuration are that all four propellers have to assume as generators of lift and thrust at the same time. That should not be achieved in higher speed flights, in addition, the character of self-stability this configuration is dependent on control algorithms. So, the idea of a composite configuration between a quadrotor and a fixed-wing models allows the integration of precious advantages of both types of models. S. Verling and J. Zilly presented a configuration of a VTOL Glider [1]. M. Hochstenbach and C. Notteboom developed a quadcopter tail sitter, named VertiKUL [2]. As the result, the concept has capability to perform not only vertical take-off and landing as a pure quadcopter, but also to fly as a fixed-wing/flying-wing configuration. Therefore, after taking off vertically at regime of a pure quadcopter and reaching at the certain altitude, the small UAV will gradually have tilted to have the horizontal velocity, and then the generation of lift will be the responsibility of its wing. In this regime, the

entire power generated by four rotors will be transferred to the thrust forces so that this concept can take advantage of high speed in comparison with the traditional form of a similar fixed-wing/flying configuration.

This research emphasizes the use of XFRL5, XFoil [3][4][5][6], the multi-fidelity analysis tools for the selection of a suitable flying-wing configuration at its cruising speed (the configuration of the quadcopter is done before and is simplified by a distribution of its payload).

2. Airfoil Selection Loop

We will identify the criteria for this UAV flying wing by using the airfoil database loop. Weighted Scoring Method (WSM) is employed for finding maximum weighted value from a collection of the suitable airfoils. So, the airfoil has maximum weighted score is selected.

2.1. UAV Airfoil Database

The Table 1 presents a collection of the 29 airfoils for our small UAV flying wing [7][8][9]. Note that, the Reynolds number (Re) in this case is about 3×10^5 (where $Re = \rho V c_w / \mu$).

Table 1. Collection of UAV flying-wing airfoil.

No.	Airfoil	No.	Airfoil
1	E182	16	HS 3.4/12B
2	E184	17	HS 3.0/9.0B
3	E186	18	HS 2.0/8.0
4	EH 1.0/9.0	19	HS 520
5	EH 2.0/10	20	HS 522
6	EH 2.5/10	21	HS 130
7	EH 3.0/12	22	S 5.0/1.0
8	MH 32	23	S 5.0/2.0
9	MH 45	24	SD 7003
10	MH 60	25	SIPKILL 1.7/10B
11	MH 60-12%	26	JWL-065
12	TL 54	27	EMX-07
13	TL 55	28	RS 400A
14	TL 56	29	PHONIX
15	HS 3.0/8.0B		

2.2. Criteria for UAV Flying-Wing

A set of criteria for the best performance of a small UAV have to be set in order to select the best airfoil. Therefore, from our UAV flying-wing design requirements, the criteria for each parameter are shown in Table 2.

Table 2. Criteria for flying wing airfoil selection.

No.	Coefficient	Criteria	%
1	C_{l0}	Close to $C_{lcrulse}$ is the best	10%
2	C_{m0} at 0 deg	Low magnitude is best	5%
3	C_m at 2 deg	Low magnitude is best	15%
4	C_{lmax}	Highest is the best	20%
5	α_{stall}	Highest is the best	15%
6	C_{dmin}	Lowest is the best	15%
7	C_l/C_dmax	Highest is the best	10%
8	$C_l^{3/2}/C_dmax$	Highest is the best	10%
Total			100%

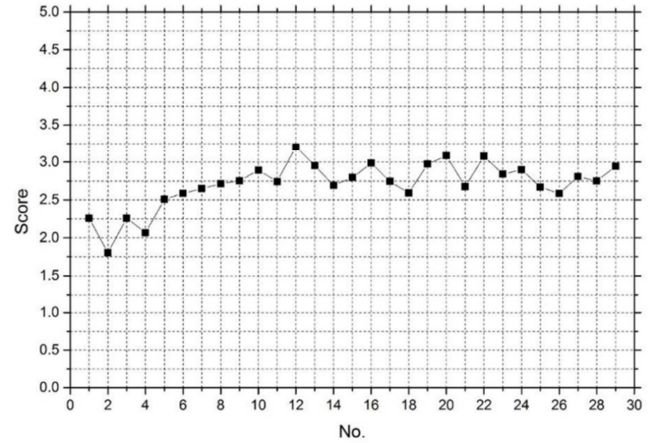
2.3. Weight Scoring Method

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.

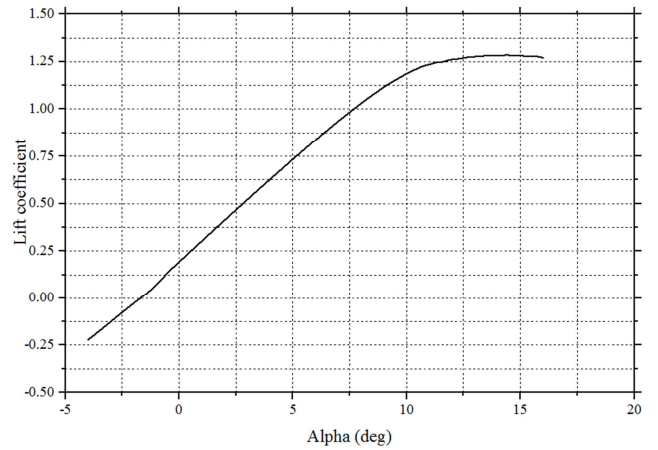
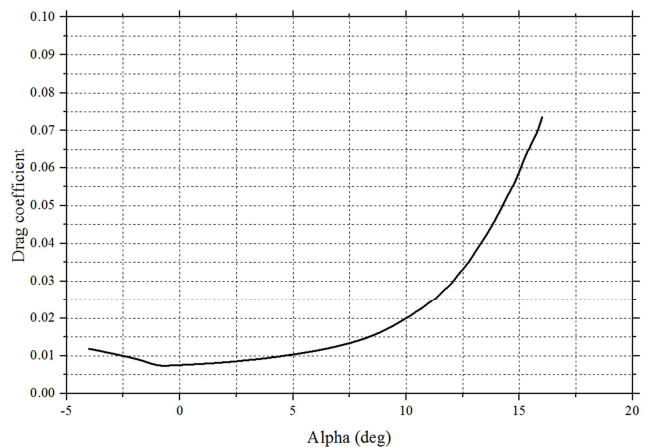
WSM consists of these following steps:

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

As shown in Figure 1, the TL54 airfoil (airfoil no. 12) have maximum weighted score, so TL54 is selected for our UAV flying-wing.

**Figure 1.** Score of Airfoil database for UAV flying-wing.

In the following figures, the aerodynamic characteristics of the selected airfoil (the TL54 airfoil) will be presented. They are the lift coefficient (see Fig. 2), the drag coefficient (see Fig. 3), the moment coefficient (see Fig. 4), the coordinates (see Fig. 5) of the TL54 airfoil.

**Figure 2.** Lift coefficient of TL54 airfoil.**Figure 3.** Drag coefficient of TL54 airfoil.

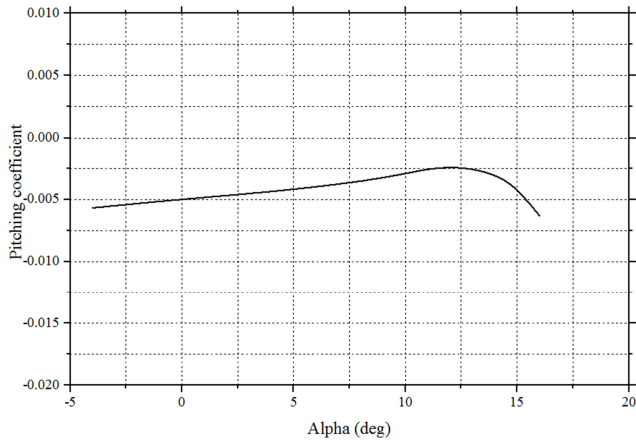


Figure 4. Moment coefficient of TL54 airfoil.

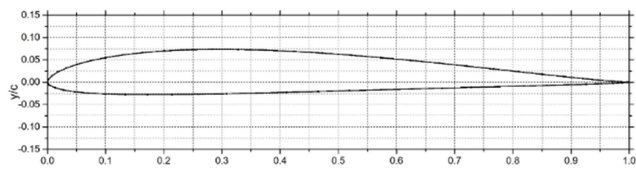


Figure 5. Coordinates of TL54 airfoil.

3. Preliminary Sizing

Based on the UAV requirements and the selected airfoils in the precedent phase, the preliminary sizing give the initial configuration of the UAV [10]. Table 3 shows the preliminary sizing of our UAV combined between flying-wing and quadrotor (note that, in this phase the configuration of the quadrotor is simplified by its payload).

Table 3. Preliminary sizing of the UAV flying-wing.

Parameters	Value
Flying weight	2.30 kg
Speed range	hover – 30.40 m/s
Range	10 km
Flight time	20÷30 minutes
Propulsion	Electric prop. (×4)
Dimensions	1.20×0.80×0.36 m
<i>Main wing:</i>	
Span of wing	1.19 m
Airfoil	TL54
Wing Area	0.22 m ²
Chord Root-Cr	0.35 m
Chord Tip-Ct	0.10 m
MACw	0.20 m
Aw	6.5
Aileron (Flap trim up 4 deg)	2.0 deg
Sweep angle	17.0 deg
Center of gravity (X; Y; Z)	(0.15; 0; 0)
Neutral point (X; Y; Z)	(0.18; 0; 0)
<i>Vertical tail:</i>	
Span	0.80 m
Airfoil	NACA 0010
Area	0.04 m ²
Chord root	0.13 m
Chord tip	0.05 m
Sweep angle	21.0 deg

4. Aerodynamic Analysis with XFLR5

Our research presented in [5] verify that the use of a multi-fidelity analysis tool like XFRL5 could help to evaluate the aerodynamic characteristics of the low speed UAVs with higher fidelity than the use of the conventional aerodynamic approach [11]. Therefore, based on the preliminary sizing, a 3D model of our UAV flying-wing is created and analyzed by XFLR5 (see Fig. 6).

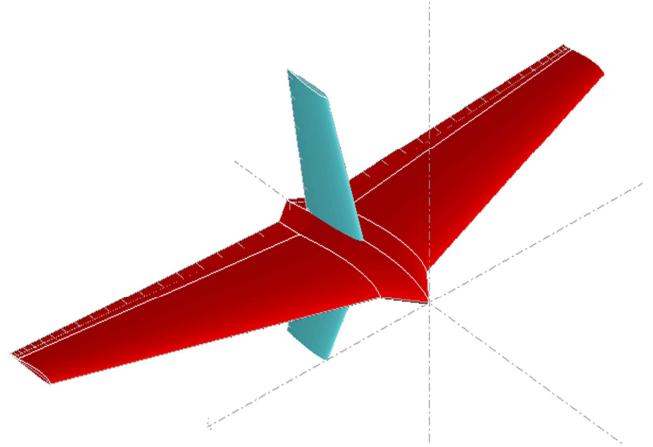


Figure 6. 3D model of the UAV flying-wing in XFLR5.

4.1. Longitudinal Stability

An airplane satisfies the static longitudinal stability if its pitching moment curve has a negative slope ($dC_m/d\alpha < 0$) and to trim at positive angle of attack ($C_{m0} > 0$). The pitching moment for an airplane could be expressed by the following equation:

$$C_{mCG} = C_{m0} + dC_m/d\alpha \times \alpha \quad (2)$$

As a result, with an airplane's configuration, the longitudinal stability could help to determine to the airplane's center of gravity position in which it is still stable. For our UAV flying-wing, the center of gravity is located at the position of 0.15 meters from the leading edge of the wing root chord ($\approx 19.4\%$ MAC) as shown in Fig. 7.

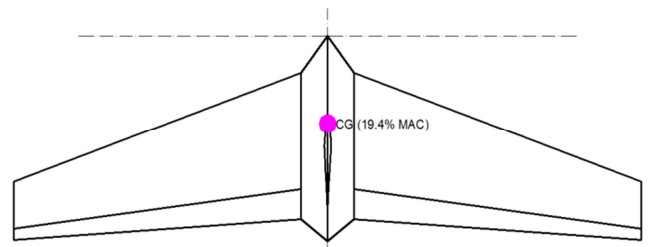


Figure 7. Center of gravity position of UAV flying-wing.

The total lift coefficient vs. angle of attack, the pitching moment coefficient vs. angle of attack will be presented in figures 8, 9. The pitching moment characteristics of this UAV flying-wing at CG of 19.4% MAC and at its cruising speed have shown that our UAV flying is satisfied with the longitudinal stability conditions. So, the slope of the lift

curve ($C_{L\alpha}$) is about 0.075 (1/deg) and the value of the zero lift angle of attack (C_{L0}) is nearly zero (see Fig. 8). The slope of the pitching moment curve ($C_{m\alpha}$) is -0.012 (1/deg) and the value of the pitch moment at the zero angle of attack (C_{m0}) is 0.014 (see Fig. 9).

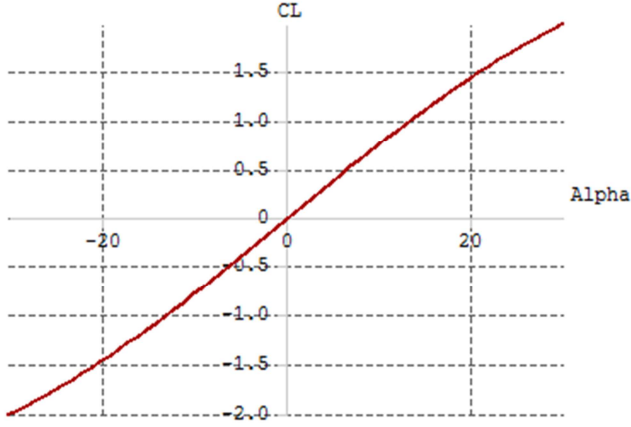


Figure 8. Total lift coefficient of UAV flying-wing.

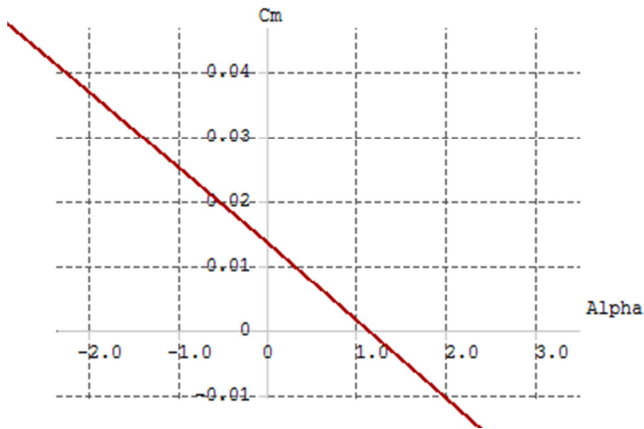


Figure 9. Pitching moment coefficient of UAV flying-wing.

4.2. Directional Stability

To have static directional stability, the yaw moment must develop a yawing moment that will restore the airplane to its equilibrium state. Assume that the airplane is flying with positive sideslip angle β , the airplane should develop a restoring moment that will tend to rotate it back to its equilibrium condition; that is, a zero sideslip angle. That means the slope of yawing moment curve ($C_{n\beta}$) must be positive [11]. Figure 10 presents the yawing moment coefficient curve of our UAV flying-wing at the CG of 19.4% MAC and at its cruising speed. With the slope of the yawing moment curve ($C_{n\beta}$) is about 0.0006 (1/deg), our UAV flying-wing is satisfied the static directional stability condition.

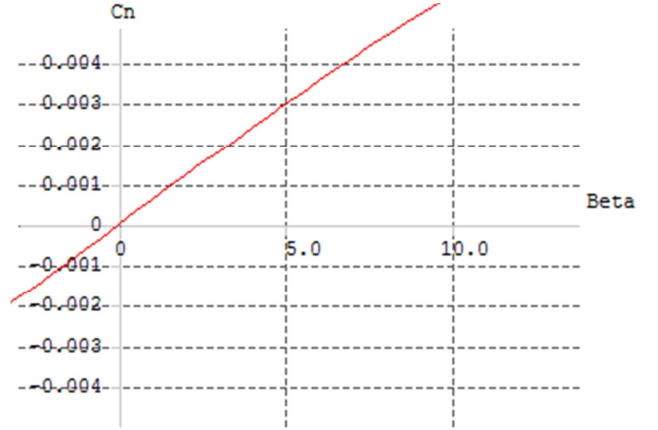


Figure 10. Yawing moment coefficient of UAV flying-wing.

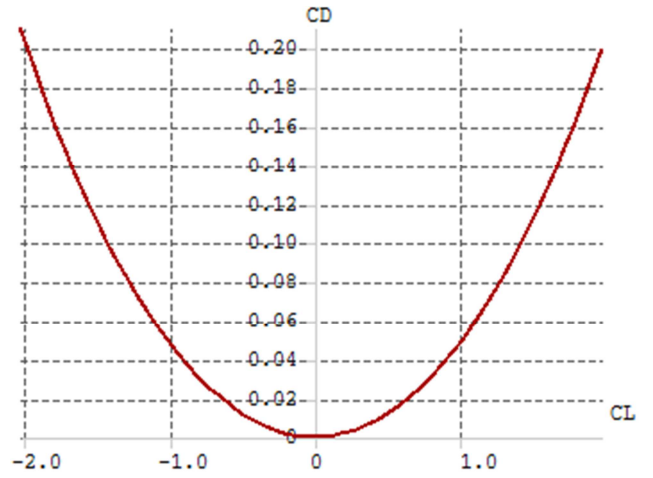


Figure 11. Induced drag coefficient of UAV flying-wing.

4.3. Drag polar

Finally, according to the preliminary sizing, the drag polar characteristics of our UAV flying-wing could be estimated in order to analyze its flight performance. The drag polar of a low Reynolds UAV has the following form:

$$C_D = C_{D0} + C_{Di} = C_{D0} + \frac{C_L^2}{\pi A e} \quad (2)$$

where C_{Di} is the induced drag coefficient and C_{D0} ($\approx C_L^2/\pi A e$) is the parasitic drag coefficient.

Because the XFRL5 is an analysis tool for planes operating at low Reynolds numbers and is based on the code in inviscid mode using 3D panels over the range $-8^\circ \leq \alpha \leq 12^\circ$, XFRL5 could only produce a good estimation of the induced drag coefficient (C_{Di}). It lack the capability for the estimation of the parasitic drag coefficient (C_{D0}). Roskam in [12] presents a simple approach according to a configuration of an airplane to evaluate its drag polar (including the parasitic drag). However, when we applied this approach to our UAV flying-wing, the value of the parasitic drag coefficient is very small in comparison with the selection of the electric motor/propeller of the similar small UAVs flying-wing. So we need to use other methods or tools with higher

fidelity to analyze the parasitic drag of the UAV flying-wing.

The figures 11, 12 present the induced drag coefficient curve and the simulation of the air flow over the UAV flying-wing at its cruising speed.

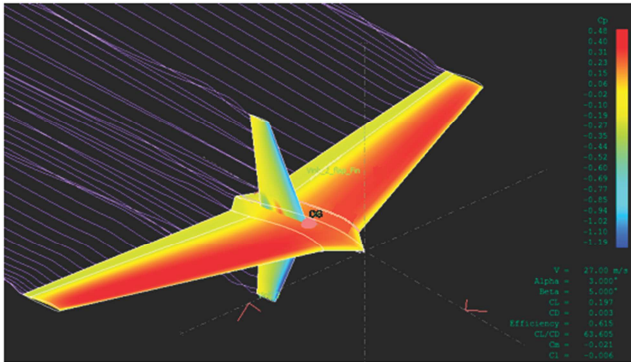


Figure 12. Simulation of the air flow over the UAV flying-wing and the distribution of pressure

5. Conclusions

A small UAV combined between flying-wing and quadrotor is a very complex product, so the design process of this UAV requires a thorough and circumspect review in order to optimize the design and to carry out the testing of the feasibility of design requirements with the lowest cost and time savings. For that reason, our research emphasizes the use of XFRL5, a multi-fidelity analysis tools, combined with an adequate airfoil selection approach for the selection of a suitable UAV flying-wing configuration in the regime of forward flight.

The limit of our work is the lacking of the capability to estimate the parasitic drag coefficient in order to evaluate the performance of our UAV. This is one of the future work in this research. Another future work is to study the stability/control of our UAV for autonomous parcel delivery with transition from vertical take-off to forward flight.

Acknowledgment

This paper is supported by VSKYLINE Ltd. in the project of designing a small unmanned aerial vehicle for surveillance.

Nomenclature

C_L	Overall lift coefficient of an airplane
$C_{L\alpha}$	Overall lift-curve slope of an airplane
C_{L0}	Zero lift angle of attack
C_D	Overall drag coefficient of an airplane
C_{mCG}	Pitch moment coefficient
$C_{m\alpha}$	Pitch-moment-curve's slope
C_{m0}	Zero pitch-moment angle of attack

$C_{n\beta}$	Yaw-moment-curve slope
ρ	Air density
C_{D0}	Parasitic drag coefficient of an airplane
c_w	Mean chord
μ	Air dynamic viscosity
C_{Di}	Included drag coefficient of an airplane
A	Aspect ratio of the main wing

References

- [1] S. Verling, J. Zilly, *Modeling and Control of a VTOL Glider*, Bachelor thesis, ETH, Zurich, 2013.
- [2] M. Hochstenbach, C. Notteboom, *Design and control of an unmanned aerial vehicle for autonomous parcel delivery with transition for vertical take-off to forward flight*, Bachelor thesis, KU Leuven, Belgium, 2014.
- [3] <http://www.xflr5.com/xflr5.htm>, XFLR5 V 6.09.
- [4] M. Drela, "XFOIL: An analysis and design system for low Reynolds number airfoils". In T. J. Mueller, editor, *Low Reynolds Number Aerodynamics*. Springer-Verlag, Jun 1989. <http://web.mit.edu/drela/Public/web/xfoil>
- [5] Anh Bao DINH, Khanh Hieu NGO, Nhu Van Nguyen, *An Efficient Low-Speed Airfoil Design Optimization Process Using Multi-Fidelity Analysis for UAV Flying Wing*, Journal of Science & Technology Development, Vietnam National University, Ho Chi Minh City (accepted 05/2016).
- [6] Ngo Khanh Hieu, Huynh Thien Loc, *Airfoil Selection for Fixed Wing of Small Unmanned Aerial Vehicles*, AETA2015: Recent Advanced in Electrical Engineering and Related Sciences, Ho Chi Minh City, Vietnam, 2015.
- [7] Michael S. Selig, Christopher A. Lyon, Philippe Giguère, Cameron P. Ninham, and James J. Guglielmo, *Summary of Low Speed airfoil data _Volume 2*, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, 1996.
- [8] Christopher A. Lyon, Andy P. Broeren, Philippe Giguère, Ashok Gopalathnam, and Michael S. Selig, *Summary of Low Speed airfoil data _Volume 3*, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, 1997.
- [9] Gregory A Williamson, Bryan D. McGranahan, Benjamin A. Broughton, Robert W. Deters, John B. Brandt and M. S. Selig, *Summary of Low Speed airfoil data _Volume 5*, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, 2012.
- [10] Ngo Khanh Hieu, Bui Khac Huy, *Electric RC Model Airplane carrying payload up to 300 grams: Design and Manufacture*, the 4th AUN/SEED-Net Regional Conference in Mechanical and Aerospace Technology, Ho Chi Minh City, Vietnam, 2012.
- [11] Robert C. Nelson, *Flight Stability and Automatic Control*, McGraw-Hill Education, 2nd edition, 1997.
- [12] Roskam, *Method for Estimating Drag Polars of Subsonic Airplanes*, Aviation and Engineering corporation, 1983.

Biography



Ngo Khanh Hieu (1978, HCM City) 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, Educator.

Head of the Aerospace Engineering Lab., HCM City University of Technology.



Pham Quang Vinh (1993, Daklak) Senior of Aeronautical Engineering – Ho Chi Minh City University of Technology, Faculty of Transportation Engineering. Work Experience:, R&D, Researcher, 2 presentations on conferences.



Dinh Anh Bao (1991, HCM City) 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)