International Micro Air Vehicle Conference and Flight Competition (IMAV2013)
17-20 September 2013, Toulouse, France

Aerodynamic Investigation and Analysis of Wingtip Thickness's Effect on Low Aspect Ratio Wing

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Abstract

In this present work, the tailless fixed-wing MAV, KUMAV-001, which is an in-house built low-aspect-ratio monoplane with span of 45 cm, aspect ratio of 1.07, and Eppler-212 airfoil section, will be used as a study case. The Eppler-212 airfoil has thickness about 10% of chord and it provides enough space at the central part. In this paper, the aerodynamics of the KUMAV-001 MAV operating at Re of 250,000 is studied. The effects of the maximum thickness variation of the Eppler -212 airfoil at wing tip are investigated. Analyses of the overall wing aerodynamic performance are explored using computational fluid dynamic (CFD) commercial software and wind tunnel tests. All longitudinal aerodynamic characteristics will be computed and measured. Referenced experimental data are used to validate the CFD simulation. Results indicate that, at low angle of attack condition, the aerodynamic performance (lift-to-drag ratio) can be improved by thin wingtip design. At high angle of attack condition, however, implementing the thin wingtip design does not appear to be effective in increasing lift-to-drag ratio.

1 Introduction

Micro Air Vehicle (MAV) is a small flying vehicle which usually flies in low Reynolds number regime. Due to the constraint of size, most fixed-wing MAVs are commonly designed with low- aspect-ratio tailless wing configuration. Fuselage is generally combined to host all equipment and payloads. Though the low-aspect-ratio wing provides very high stall angle of attack (AOA), it introduces high induced drag due to the effect of tip vortices. Furthermore, aerodynamic performance of wings in low Reynolds number regime is typically low because of unexpected flow separation. An interference drag between wing and body also plays an important effect. Accordingly, these result in a reduction of MAV's aerodynamic performance. Therefore, one of the challenges for aerodynamic and design of MAV is to improve lift-to-drag ratio (L/D) of overall vehicle. Generally, thin airfoils give better aerodynamic performance [1] and hence suitable for MAV design. However, using of the thin wing design has a drawback of limited space required for housing all equipment and payloads. The fuselage must be added leading to an increment of the interference drag. Thus, an idea of utilizing thick airfoil at root for installing components while decreasing the wing thickness on the outboard part to improve aerodynamic performance of the wing is proposed.

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Figure 1: KUMAV-001 Design

Airfoil	E212	Max. Thickness	10.55
Root chord	45 cm	Tip chord	39 cm
Aspect ratio	1.07	Span	45 cm
LE swept	17 deg	Dihedral	0 deg
Control surface	20% root chord	Flight speed	7-15 m/s

Table 1: Design configuration of KUMAV-001

MAV activity in Kasetsart University (KU) has started since 2010. The first MAV, named KUMAV-001, has been constructed and tested. KUMAV-001 design consists of propulsive tractor with elevon configuration. It has 45cm-span, aspect ratio of 1.07 and Eppler-212 airfoil section. The baseline wing model came from the monoplane wing studied by Arizona State University (ASU) [2]. Fuselage is added in order to install battery and other components. A year later, the effects of winglet on MAV performance have been investigated by Thipyopas and Intaratep [3]. Wind tunnel and flight test were conducted to study the propwash effect to the wing. The design and study of KUMAV-001 was presented in the IMAV2011 conference. The KUMAV-001 is illustrated in Figure 1 and summary data of design configuration are shown in Table 1. The lift-to-drag ratio (L/D) of KUMAV-001, however, is quite low like other low-aspect-ratio monoplane MAVs. To improve flight endurance, KUMAV-001 was redesigned to achieve higher L/D. Mueller [4] conducted experimental tests to compare thick and thin airfoils at low Reynolds numbers for MAVs. He found that thin airfoils give greater aerodynamic performance. Viieru et al. [5] enhanced the L/D of MAV by modification of wingtip shape. In 2008, Blanc et al. [6] studied various thickness of wing using NACA 53xx airfoil sections. The wing thickness is varied from 2% to 10% chord. The wing thickness of 2% chord gave the best result of the L/D. This suggested that thin airfoil wing is suitable for MAV design. However, reducing the wing thickness too much may result in decreasing L/D. A drawback of thin wing design is that it has no enough space for installing battery and equipment. The fuselage must be then added to accompany all the payloads. Adding the fuselage may cause the interference drag. Thus, an idea of remaining thick airfoil at wing root in order to install components while decreasing of thickness on outboard part, where no need to attach any component, is studied in this paper. Since the thickness of Eppler-212 airfoil is about 10% chord, it provides enough space at the central part. This concept may be beneficial and practical for low-aspect-ratio MAVs.

2 Methodology

This section provides the descriptions of apparatus and procedures of the wind tunnel tests and CFD simulations studied in the present work.

2.1 Wind Tunnel Tests

Five wing-only models were designed based on the design configuration as shown in Table 1. Effects of engine, fuselage, and control surfaces are neglected. The baseline wing model has a constant thickness (10.55% chord), while other four models had thickness varying from 10.55% chord at the root to approximately 8%, 6%, 4% and 2% chord at the tip, respectively. All tested models, illustrated in Figure 2, were made of foam covered by composite material for rigidity, and wrapped by thin plastic sheet for smooth surface. Figure 3 shows schematics and dimensions of the geometries for the wing model with thickness of 2% chord at the tip.

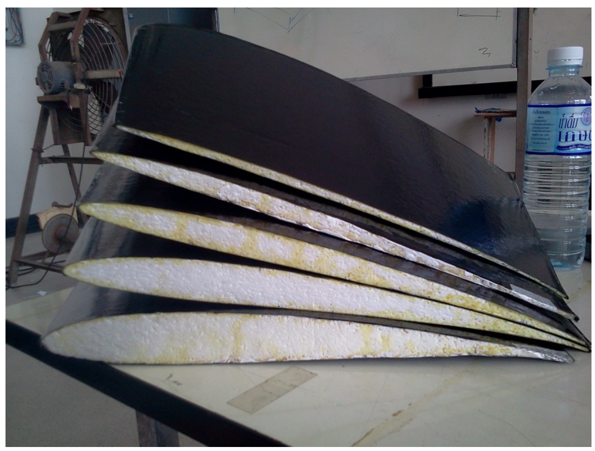


Figure 2: Test models

The aerodynamic characteristics were measured by a 3-component balance. The wing model was supported by a single strut at the mean chord position. Lift, drag, and pitching moment were obtained directly by a 3-component balance system outside the test section. The maximum capacities are ± 15 N and ± 1.5 N-m for force and moment, respectively. The accuracies of the balance for force and moment are 0.1 N and 0.02 N-m, respectively. The balance and angle of attack adjustment systems using the turn table and test setup are shown in Figure 4. All experiments were conducted in the closed-loop wind tunnel at Kasetsart University. The wind tunnel has a test section of 1m $\times$ 1m $\times$ 3m (W$\times$ H $\times$L), and a contraction ratio of 4. The maximum speed is 60 m/s generated by a 2m-diameter fan with maximum power consumption of 75 kW. The test speed presented in this study is 10 m/s only. Test speed was measured using a Pitot-static probe installed in front of the model and a digital manometer with an accuracy of 5 Pa. For the wind tunnel testing, lift, drag, and pitching moment were measured with angle of attack ranged between -9 and 36 degrees. Data correction was performed for the wind tunnel test data. The standard blockage and wall correction of Barlow et al. [7] was applied to the primary measured data. The schematics of the wind tunnel are shown in Figure 5.

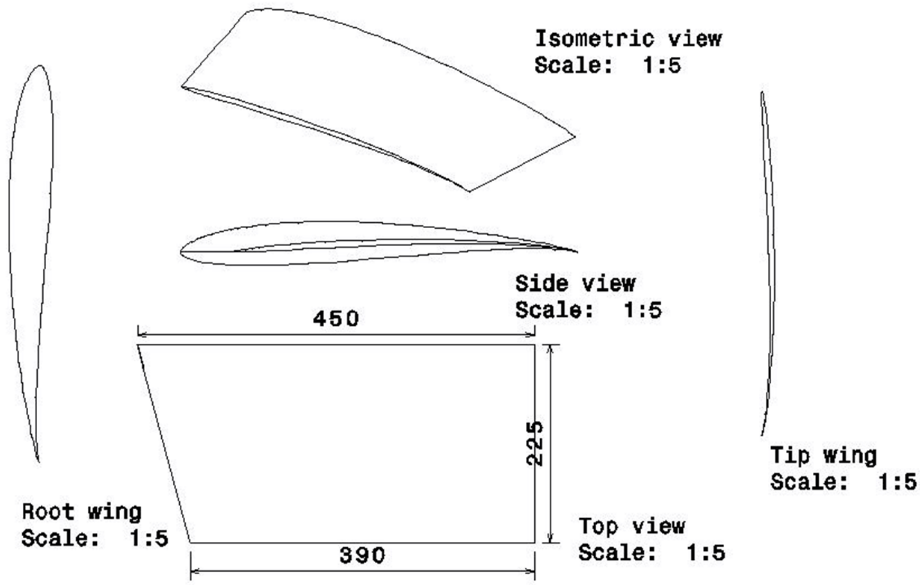


Figure 3: Geometry for a wing model with tip thickness of 2% chord

Figure 4: 3-component balance with turn table and model setup

Figure 5: Schematic views of Kasetsart University wind tunnel

2.2 CFD Simulation

In this present study, all CFD simulations were performed with a CFD commercial solver FLUENT^{TM} 6.3. Flow fields were simulated and analyzed with three-dimensional steady incompressible Reynolds-Averaged Navier-Stokes (RANS) simulations at Reynolds number of 250,000. To simulate the effect of turbulence, the Spalart-Allmaras one-equation turbulence model was used. Five different wing geometries were modeled and the computational grids were generated with structured mesh as shown in Figure 6. The grid is clustered in the vicinity of the wing surfaces, the trailing edge, and the wing tip to accurately capture the effects of tip vortices and trailing edge wakes. The far field boundaries are placed approximately 10 chords upstream and 20 chords downstream the wing. The far field boundary in spanwise direction is located approximately 10 half-span of the wing away from the tip.

On the upstream and far field boundaries, a velocity inlet condition is imposed with axial velocity Vx = 10 m/s. On the downstream boundary, a pressure outlet condition is imposed with pressure of 101,325 Pa. Wall conditions (no-slip conditions) are imposed on the wing surfaces. A symmetry condition is imposed on the mid-span plane to simulate the effect of another half wing. The reference values for these simulations are: freestream temperature T_∞ = 288.16 K, freestream density ρ_∞ = 1.225 kg/m^3, reference chord length c = 0.42 m, and reference wing area = 0.0945 m^2. Validation of CFD simulation was performed. The grid-independence study yields a reasonable good mesh of 4.28×10^6 grid points to be used in further simulations.

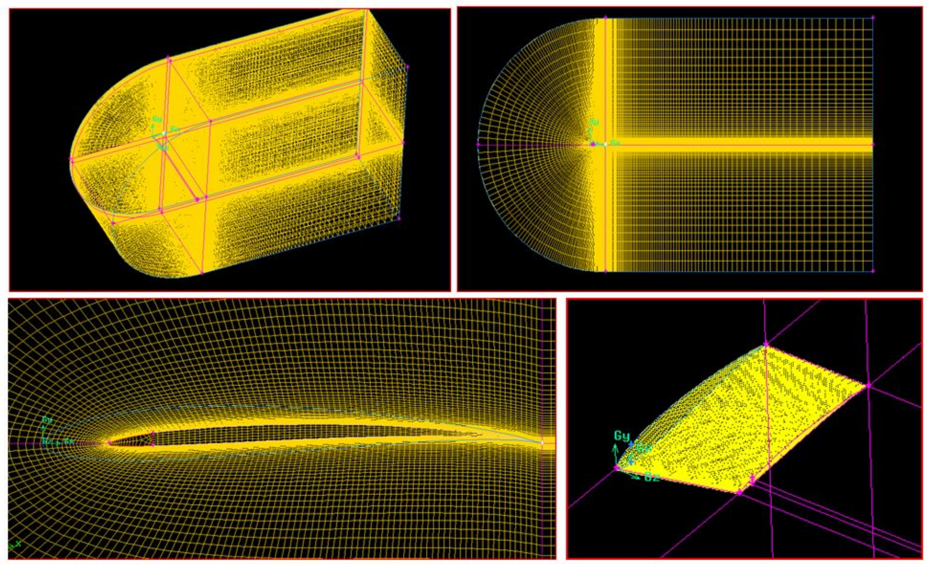


Figure 6: 3D structured grid for CFD simulations

3 Results and Discussion

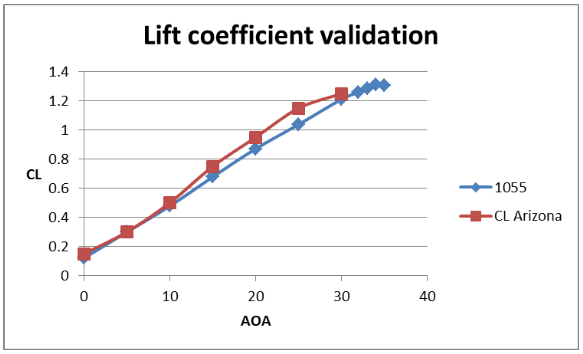
The following wind tunnel and CFD results have been obtained for the several wing configurations at a flight speed of 10 m/s (Re = 250,000) and at angles of attack ranged from -10 (from 0 in CFD) to 35 degrees. The effect of wingtip thickness on wing aerodynamic performances was studied by comparing the predicted lift coefficient (C_L), drag coefficient (C_D), pitching moment coefficient (C_M), and lift-to-drag ratio (L/D) of the modified wings with the baseline wing. For the following results, the numbers showed in the plots refer to the wingtip thickness in percentage (with 2 decimals) of root chord length; for example, '1055' means 10.55%c thickness, '396' means 3.96%c thickness

3.1 Validation of CFD Solver

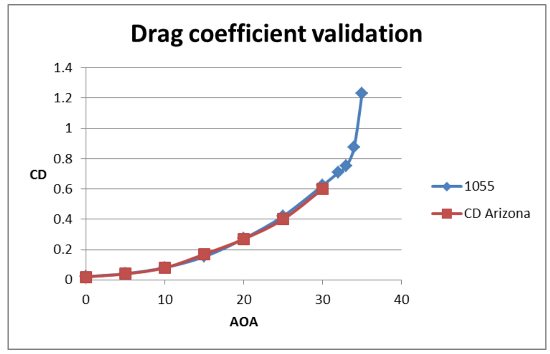
Prior its further use to investigate wing models with various thicknesses, the flow solver has been validated for the baseline wing (10.55%c thickness) with reference data from the study of Arizona State University (ASU) [2]. To validate the solver, plots of lift coefficient and drag coefficient varied with angle are given in Figure 7. It is clearly seen that the validation gives a reasonable good agreement between CFD results and experiments.

3.2 Effects of Wingtip Thickness on Aerodynamic Performances

Figure 8 shows the variations of lift coefficient as a function of angle of attack (AOA). Experiments and simulations clearly show that the thickness of wingtip has strong effect on aerodynamic performance of the wing, particularly at high AOAs. For the thinner wingtip, the lift coefficients are higher relative to the baseline constant-thickness wing. It is also seen that lift curve slope increases as wingtip thickness decreases. The wind tunnel results appear to have some non-linearity in the lift curve slope possibly due to some uncertainty in the angle of attack. The wings with thinner tip have lower stall angle of attack. At low AOAs, both measurements and CFD predictions indicate that the wingtip thickness has insignificant influence on aerodynamic performances.

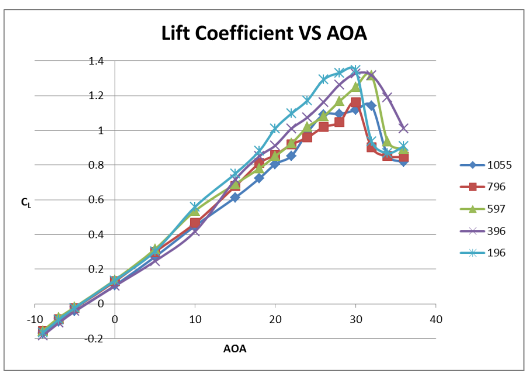


(a) Experiment

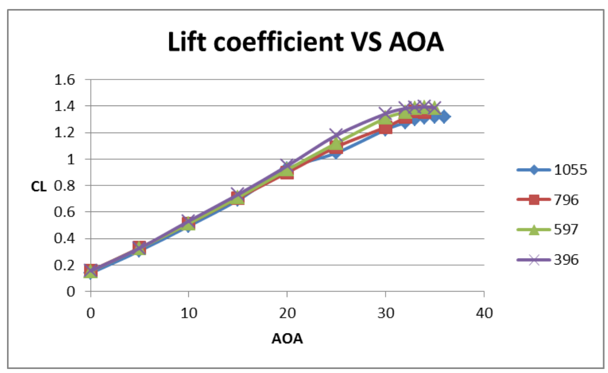


(b) CFD

Figure 7: Comparison of lift and drag coefficients at Re = 150,000 (Blue line: CFD results, Red line: Data from ASU)



(a) Experiment

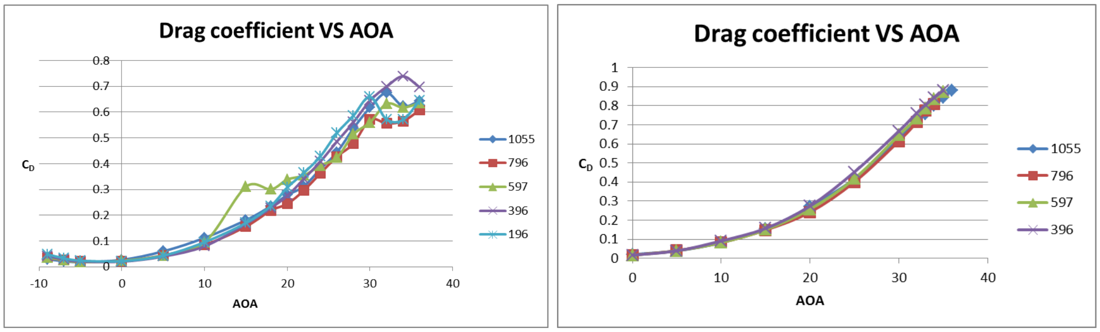


(b) CFD

Figure 8: Effect of wingtip thickness on lift coefficient

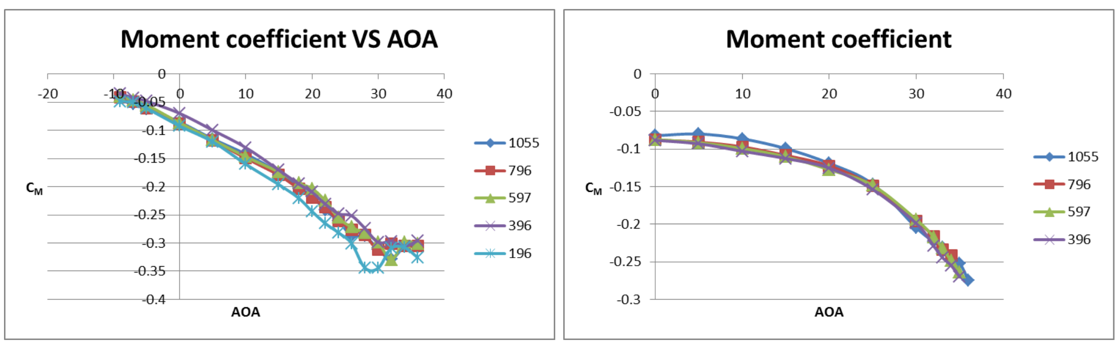
The results for the variations of drag coefficient as a function of angle of attack are presented in Figure 9. It should be noted that the drag forces are quite small and sensitive to the pressure distribution in the leading edge stagnation region, and trailing edge recompression region. The qualitative agreement between the measurements and the predictions is reasonable when this uncertainty in the measurements of (C_D) is factored in. The prediction of transition also influences the prediction of skin friction drag, and can also affect the prediction of drag force. Results show that wings with wingtip of 7.96%c and 5.97%c thickness have less drag force, while other thinner wings (3.96%c and 1.96%c) yield more drag force. Thus, no clear conclusion can be drawn for the effect of wingtip thickness on drag force.

Figure 10 presents the variations of pitching moment coefficient as a function of angle of attack. Results show that wings with thinner tip have more negative pitching moment. However, the longitudinal static stability, $\partial C_M/\partial\alpha$, does not appear to be influenced by the wingtip thickness.



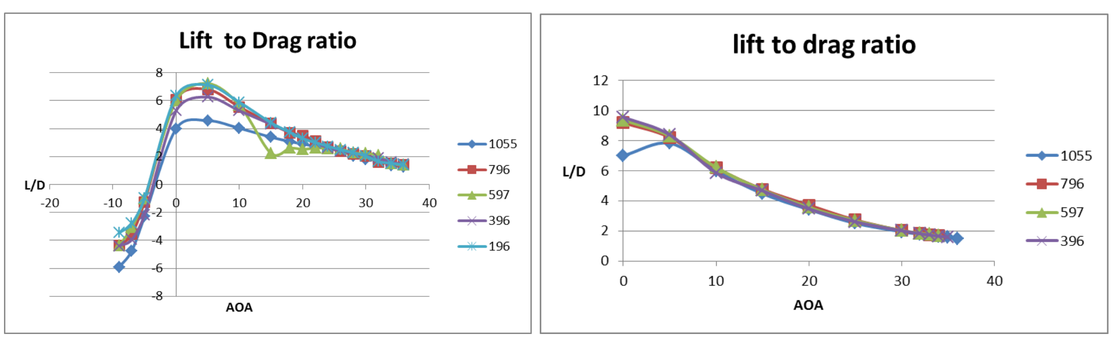
(a) Experiment (b) CFD

Figure 9: Effect of wingtip thickness on drag coefficient



(a) Experiment (b) CFD

Figure 10: Effect of wingtip thickness on pitching moment coefficient



(a) Experiment (b) CFD

Figure 11: Effect of wingtip thickness on L/D

Considering the L/D plot shown in Figure 11, both measurement and CFD results clearly reveal a strong influence of wingtip thickness on the L/D at low AOA conditions. Reducing wingtip thickness appears to improve the wing aerodynamic performance only for low AOA cases (up to 20 degrees in experiment, and up to 5 degrees in CFD simulation). For high AOA cases, reducing wingtip thickness is not as effective in improving wing performance as at the low AOA cases. In these cases, they have been found that there are insignificant changes in L/D since lift and drag are noticeably increased in experiments and CFD simulations.

4 Conclusions

The aerodynamics of a series of new design of KUMAV-001 wing has been analyzed using CFD technique and tested in wind tunnel at cruise speed condition. The conditions chosen for detailed study range from low to high angles of attack. Calculations have done using a viscous flow solver, and aerodynamic performance quantities are extracted for comparisons to experiments. Wind tunnel tests have been carried out on a series of wings of varying wingtip thicknesses. Experiment and CFD results show that, at low angle of attack condition, the wing with thin wingtip can produce a net increase in lift-to-drag ratio compared to the baseline wing. At high angle of attack condition, reducing wingtip thickness becomes ineffective in increasing lift-to-drag ratio.

5 Acknowledgement

The authors wish to thank Department of Aerospace Engineering, Faculty of Engineering at Kasetsart University for financial support of this work. The authors would like to thank Mr. Kwanchai Chinwicharnam for preparing *LaTeX* file of this manuscript.

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