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The Improvement of Aerodynamic Performance of Flapping-Airfoil Using Thickness Variation Airfoil

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두께 변화가 있는 익형을 이용한 Flapping-Airfoil의 공력성능 개선

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In this work, numerical experiments are conducted to find out the optimal shape of flapping-airfoil using thickness variation airfoils. In the previous study of flapping-airfoil, we had found that the thrust efficiency of thicker airfoil is better than thinner one, but the latter has higher thrust coefficient. Therefore, we have combined thin(NACA0009) and thick(NACA0015)airfoil to overcome these demerits of each airfoil. Using this combined airfoil, we can achieve acceptable aerodynamic performances from thrust efficiency and coefficient points of view. In order to computational study, we have used parallel -implemented incompressible Navier-Stokes solver. Computational results show how to design leading and trailing edge shapes.

1. Introduction

Recently, the aerodynamic characteristics of flapping airfoils have been of major interest in the micro-aerial vehicle (MAV) design. Compared to conventional aircrafts, MAV has a very small characteristic size of 6 to 15cm and a cruising speed of 8 to 18m/s. Therefore, the flows over MAV are, in general, characterized by low Reynolds number flow compared to conventional commercial aircraft. As a result, the lift to drag ratio of MAV is approximately 20% of commercial aircrafts such as BOEING 747. In order to overcome this poor aerodynamic performance, the ornithopter type MAV with flapping motion has been proposed as a promising alternative approach. Flapping motion of wings can improve lift substantially and generate thrust with an unsteady flying mode. The flight mechanism of flapping motion can be frequently observed in the flight of insects and birds in low Reynolds number flow regime.

2. Numerical approach

Aerodynamic characteristics flapping airfoil in low Reynolds number flows are numerically studied using the unsteady, incompressible Navier-Stokes flow solver. Eqn. 1 is Two-dimensional governing equations in which were spatially discretized with Osher's upwind differencing scheme. In order to time integration, Yoon's LU-SGS scheme was used. And pseudo-time method was used to unsteady time evolution. For more efficient computation of unsteady flows over flapping airfoil, the flow solver implemented with MPI parallel programming method. To apply flapping motion of airfoil, and describe flow fields more precisely, we also adapted moving mesh technique and two-equation turbulence modeling.

$$\nabla \cdot \vec{v} = 0$$

$$\frac{D\vec{v}}{Dt} + \vec{v}_a \cdot \nabla\vec{v} + \nabla p = \nabla \cdot \sigma \tag{1}$$

$$\frac{D\vec{v}}{Dt} = \frac{\partial \vec{v}}{\partial t} + \vec{w} \cdot \nabla\vec{v}$$

$$y(t) = h \cdot \sin(kt) \tag{2}$$

$$\alpha(t) = \alpha_0 \cdot \sin(kt + \phi) \tag{3}$$

Eqn. 2, 3 describe flapping motion of airfoil. Eqn. 2 is pitching motion. Eqn. 3. plunging motion.

3. Numerical Results

A parallel-implemented incompressible flow solver named IFANS2D[1] is used to compute the unsteady flows over the NACA four-digit airfoils. The Reynolds number based on chord is 12,000. The computational grid is 245 × 125 hyperbolic O-grid with the wall spacing order of 10^{-5}. The flapping is analyzed by the superposition of pitching and plunging motion.

Firstly, we have simulated the pure pitching motion about NACA0012. Fig. 1 shows that present results yield a better agreement in thrust at various reduced frequency

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with Koochesfahani's experimental data[2]. Also, drag to thrust conversion frequency is very close to experimental result. It is known that inverse Kármán vortex street shed from airfoil tip feeds momentum to air and its reaction force exerts to airfoil. The above mentioned situation is shown in the Fig. 2. This jet-like flow feature is major mechanism of thrust generation in flapping motion of airfoil. But, moment coefficient versus angle of attack is show that pure pitching motion is inherently unstable mode of flight mechanism as shown Fig. 3. This upstroke motion lead positive moment coefficient and downstroke lead negative one.

Secondly, for the same flow condition of pure pitching motion, the pure plunging motion case is also studied. Pure plunging motion is turned out to be less efficient than pure pitching motion as shown in Fig. 4. The reason is due to the leading edge separation by increasing effective angle of attack as shown in Fig. 5. A leading edge separation bubble forms a leading edge separation vortex, this absorbs supplying energy in kinetic energy manner. This physical phenomenon, however, can act favorably to the generation of lift coefficient. Also these leading edge separation vortex can disturb trailing jet-like flow region. In the both pitching and plunging cases, we can't found a difference of laminar between fully turbulence assumed flow results.

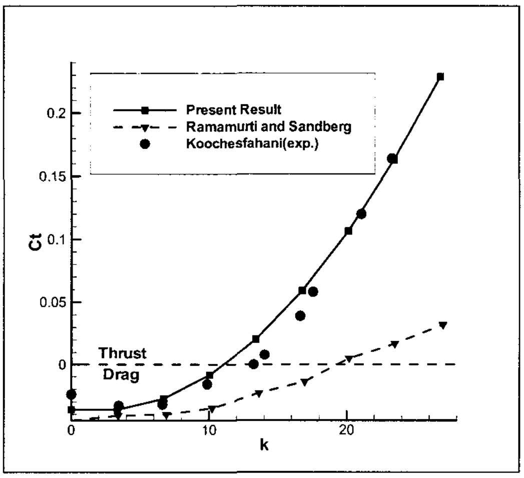

Fig. 1. Thrust as a function of Reduced frequency

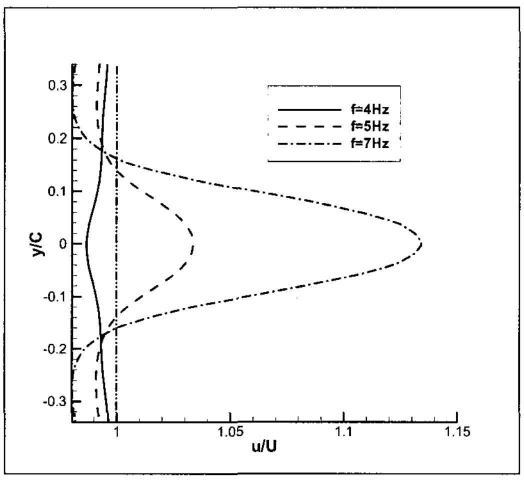

Fig. 2. Velocity profile

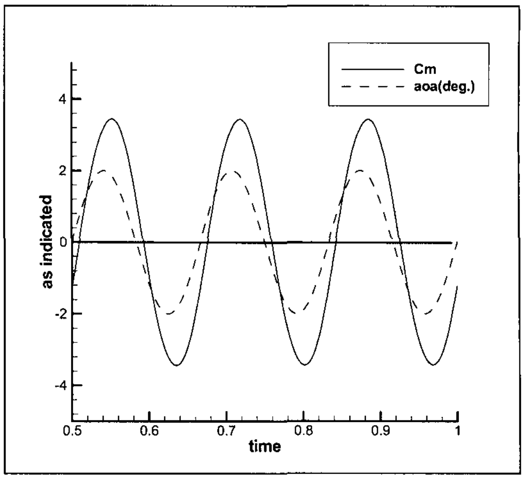

Fig. 3. Moment coefficient vs Pitching Motion

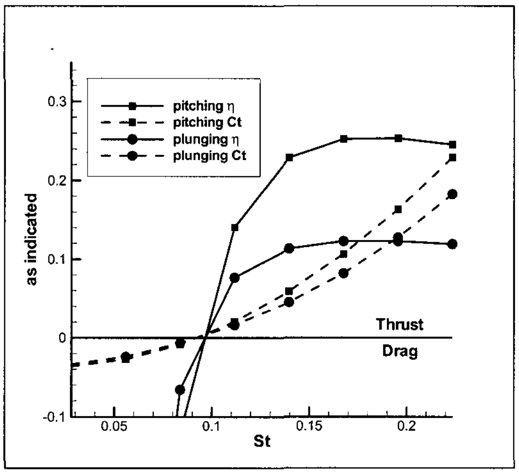

Fig. 4. Thrust as a function of Reduced frequency

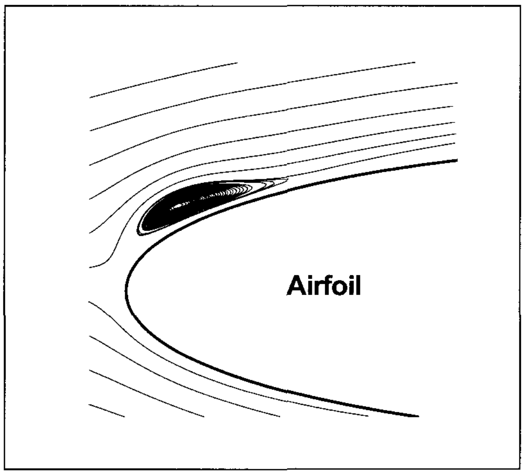

Fig. 5. Thrust as a function of Reduced frequency

Finally, flapping motion has the capability to generate thrust better than previous two motions. Fig. 6 show the thrust coefficient which is Comparison each motion case. To investigate the effects of geometric changes on thrust mechanism, we use NACA four-digit airfoils. Computed results in Fig. 7 show that thickness growth yields quite a positive influence on thrust, while a negative influence on efficiency. Increase in camber causes poor aerodynamic performance in shown Fig. 8,9. We thus conclude that the leading edge separation, its shedding vortex or inverse Kármán vortex street shedding from the airfoil tip are related to the major mechanism of flapping airfoil. Therefore, these vortexes control is the key point in the development of an ornithopter type MAV. Ct is thrust coefficient, η is thrust efficiency.

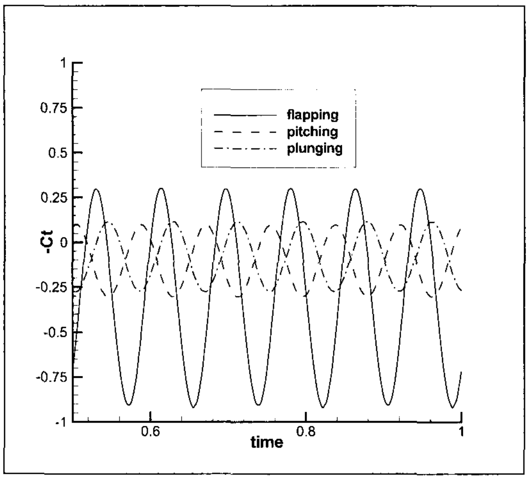

Fig. 6. C_t versus time.

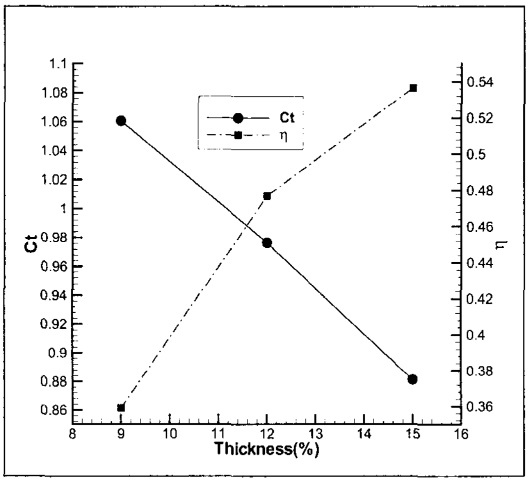

Fig. 7. Thickness effect.

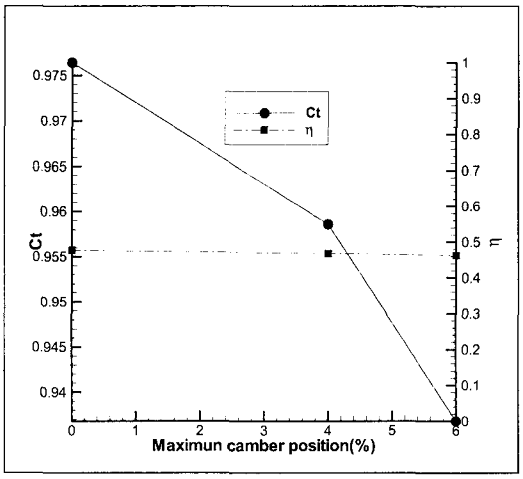

Fig. 8. Maximum camber position effect.

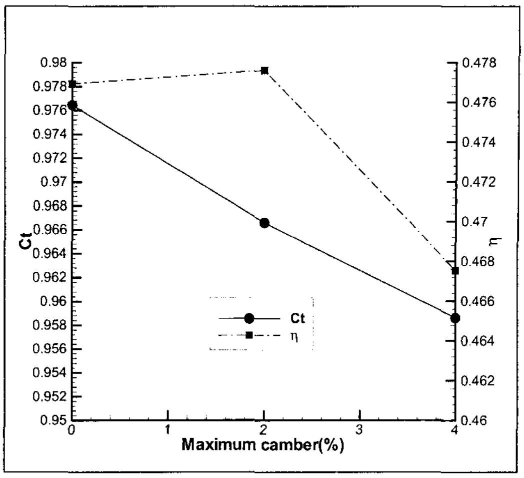

Fig. 9. Maximum camber effect.

4. Modification of airfoil shape

As shown in Fig. 7, we can see the aerodynamic characteristic of airfoil thickness effect, the thicker one has merit on thrust efficiency, but thinner can generate more thrust force. This is reason that leading edge separation bubble. So, we have combined two airfoil, leading part is NACA0015, trailing part is NACA0009 as shown in Fig. 10. The numerical results are shown in table 1, it show that the modified airfoil has better aerodynamic performance. Thick leading edge prevent leading edge separation vortex. Thus thrust efficiency increased. Further, thin trailing edge make stronger pressure gradient in the rear region. So this pressure gradient can make stronger vortex, thrust efficiency is more increased.

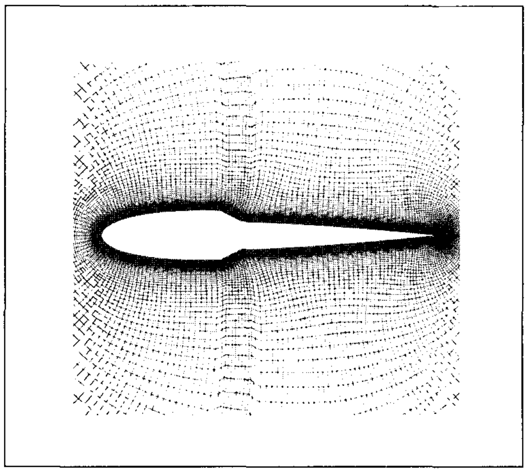

Fig. 10. Combined airfoil

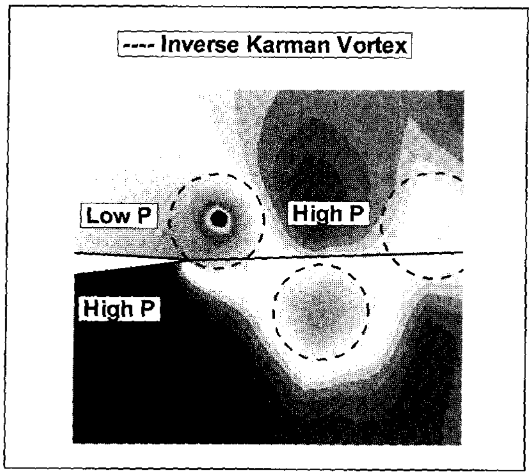

Fig. 11. Maximum camber effect.

	NACA0 009	NACA0 012	NACA0 015	Combined
Ct	**1.060**	0.976	0.881	**1.016**
η	0.359	0.474	**0.536**	**0.521**

Table 1. Aerodynamic performance

5. Conclusion

In this research, we performed numerical analysis with Navier-Stokes solver to investigate aerodynamic characteristics of airfoils with flapping motion and fixed wing of SNU MAV. In flapping motion analysis, it is composed of pitching and plunging motion. It is found flow field with flapping motion is governed by two major factors, one is leading edge vortex, the other is trailing edge vortex. And these vortexes are significantly dependent on geometry of airfoils. Thus, thinner and thicker one have merits and demerits respectively. The thrust coefficient of the former is high but efficiency is not high. The latter is vice versa. Using combined airfoil, therefore, the demerits of each case can be removed.

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