The Aerodynamic Improvement of a Flexible Flapping Wing

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Abstract: Recently, various studies of Micro Air Vehicle (MAV) and Unmanned Air Vehicle (UAV) have been reported from wide range points of view. The aim of this study is to research the aerodynamic improvement of flapping wing in low Reynolds number region to develop applicative these air vehicles. The six kinds of elliptical wings made of stainless steel are used in the flapping wing. The effects of flapping amplitude and wing configuration regarding the aerodynamic characteristics are investigated in detail. The fluid force measurement by six-component load cell and PIV analysis are performed as the experimental method. In the flapping wing experiment, we tried to relate the force measurement and PIV data at the same timing by means of encoder signal from the flapping motion. The relations between the aerodynamic superiority and the vortex behavior around the models are demonstrated.

Keywords: Aerodynamic Characteristics, PIV Measurement, Flapping Wing, Leading Edge Vortex, Trailing Edge Vortex

1. Introduction

MAVs and UAVs have the potential to revolutionize our capabilities of gathering information in environmental monitoring, homeland security, and other time sensitive areas. Recent interest in these air vehicles has resulted in a need for a better understanding of flow physics and also for effective flow control strategies [1]. Experimental and computational investigations of flapping wings have been performed in abundance as favorite candidates of the air vehicles.

Birds and insects also twist and bend their wings for optimal lift and thrust while maneuvering. Clearly, wing stiffness distribution and flexibility are important aspects when considering natural fliers [2]. So, recent interest in the air vehicles has created a desire to understand flapping wing flight from the viewpoint of biomimetics.

The most important feature in wing aerodynamics has been established to be the generation of a stable leading edge vortex (LEV) on top of the wings, which increases the circulation around the wing and creates much higher lift than the steady state case [3]. Three dimensional flow effects are essential for the LEV stability. Suggestions have been forwarded as to the possible analogy between the LEV stability on flapping wing and the stable LEV generated by swept and delta wing [4].

In the flapping wing researches, experiments have focused on rigid airfoils, where the effects of oscillation mode and aspect ratio have been investigated [5]. In contrast, the effect of wing stiffness, in either the chordwise or spanwise direction, is relatively unexplored [6]. That is to say, the present motivation for this research field is to get knowledge of the deformation of the flexible wing under aerodynamic loading and the effect of that deformation on wing efficiency. The purpose of this study is to investigate the aerodynamic characteristics of flapping wings via various wing thicknesses and flapping amplitude in order to improve the aerodynamic performance of flapping wing by using high precision PIV measurement.

2. Experimental Setup

2.1 Wind tunnel

In this study, we use the Eiffel type three-dimensional open-section wind tunnel. The test section area is 0.6 m x 0.6 m, the test section length is 1.1 m, and the contraction ratio is 6.25:1. This wind tunnel is capable of a maximum flow velocity of 25 m/s. In case of the uniform flow velocity of 10 m/s, the uniformity of velocity is 1.3 %, the turbulent intensity is 0.3 %.

2.2 Flapping wing model

Fig.1 shows the flapping wing model in this study. Further, the plan view of the model is shown in Fig.2. This model has a mechanism capable of adjusting the flapping amplitude FA from 0 degree (fixed wing) to 40 degrees as shown in Fig.3. The wing is elliptical type to reduce an induced drag. We prepared six kinds of stainless steel...
wings of which the thicknesses \( t \) = 0.2 mm, 0.5 mm, 1mm, the aspect ratio defined by square of wing span to wing platform area \( AR = 6, 8 \). The root chord length \( c \) of these wings is constant of 60 mm, and these wings can be change easily.

A DC motor (RS-540SH, MABUCHI MOTOR Ltd.) is used as the drive unit of the wing. Rotation of the motor is changed into flapping reciprocating motion through hypoid gear. In this flapping device, we can adjust the flapping frequency from 0 Hz (fixed wing) to 10 Hz by PWM control. Moreover, an encoder (MES-9-900P, Micro Tech laboratory Inc.) is attached with this model to detect a flapping angle.

3. Experimental Approach

3.1 Fluid force measurement

In this study, the strain gauge type 6-component load cell (MDF-250N, Showa Measuring Instruments Ltd.) is used for measuring the fluid force such as lift and drag. The diameter of the load cell is 125 mm. The rating capacities of this load cell is 250 N for three kinds of force and 6 N for three kinds of moment in each direction. This load cell is a focus concentration type. It is designed so that 6 components are converged on one point in this load cell. In addition, it is possible in this 6-component load cell to suppress mutual interferences between respective components. This load cell is connected with the data recording apparatus (Omniae RA2300, NECAvio Ltd.), which includes three 2-channel DC strain amplifier units, to obtain the digital data of 16 bits. Fig.4 shows fluid force measurement system in this study. As the calibration of this measurement, the net fluid force acting on just only the wing is calculated by subtracting the measuring data of the model with no wing from the data of the full featured model. The sampling frequency in this measurement is 1kHz, the sampling time is 20sec. The fluid force measurement acting on the flapping wing was performed varying the angle of attack \( \alpha \) in the range from 0 to 40 degrees every one degree.

3.2 PIV analysis

In this study, we have been trying to measure the velocity field around the flapping wing by means of two types of PIV trigger measurement. The first method is temporally-discrete PIV measurement at specified flapping phase angle within one cycle of flapping motion. From this measurement, we can compare the leading edge vortex behaviors in various flapping motion conditions (named “Discrete PIV”). In the second method, trigger signal is output at the same phase angle as first method, and temporally-continuous PIV measurement is conducted by using a high speed camera (named “Continuous PIV”). By synchronizing the irradiation from laser light source with the specific flapping angle \( \theta \) detected via the rotary encoder, the effect of the flapping motion can be assessed in detail with the velocity and vorticity distributions near the wing surface and the position of the leading edge vortex core. Fig.5 shows the PIV trigger measurement system in this study.

We use oil mist generator (Flow Tech Research Inc.) and fog generator (Magunam850, Martin Inc.) as seeding equipment of tracer in this PIV measurement. The accuracy of our PIV analysis is greatly enhanced by adopting these two kinds of tracers because the oil mist particles of which average diameter is 2μm, get more
visible according to the much scattering light of the glycol particle of 5μm diameter supplied from this fog machine. The instantaneous velocity field can be obtained as a result of high acquisition rate more than 98% of velocity vectors. In the case of Discrete PIV measurement, the laser light is double-pulse Nd:YAG laser (LS-2131M, LOTIS TII Ltd.). The pulse energy of second harmonic in this laser is 125 mJ, and the wavelength is 532μm. The repetition rate of the laser in this experiment is 10Hz, and the interval of double pulse is ranging from 10μs to 20μs. The PIV camera used in this measurement is progressive scan type CCD camera in which effective number of pixels is 1.92 million (1600 × 1200). In the case of Continuous PIV measurement, we use double-pulse Nd:YLF laser (Pegasus PIV, New Wave Research). The output energy in the emission frequency of 1kHz is more than 10mJ. The repetition rate of the laser in this experiment is 1kHz, and the interval of double pulse is ranging from 10μs to 20μs same as Discrete PIV measurement. High speed CMOS camera is used in this PIV method, in which effective number of pixels is 1.04 million (1024×1024). As the solver of this PIV analysis, a direct cross-correlation method is applied. By using this method, we can obtain two dimensional in-plane velocity distributions simultaneously. The size of interrogation window is 32×32pixel corresponding to 1.78×1.78mm of real dimension in the Discrete PIV measurement. While, the size of interrogation window is 32×32pixel corresponding to 2.79×2.79mm of real dimension in the Continuous PIV measurement. The laser light sheet of 3mm thickness is obtained from the laser beam through cylindrical lens, and is adjusted so that the sheet plane is parallel to the chord direction at y/b=0.25,0.5,0.75, here b is the half of wing span, y is the distance from the wing root.

4. Result and Discussion

4.1 Fluid force measurement
In this study, the uniform flow velocity U is set to 10 m/s. The Reynolds number Re=3.12×10^{4} as the characteristic length 47.1 mm of the mean chord for this flapping wing in case of AR=8. Fig.6 shows the lift curves with angle of attack α according to flapping amplitude and wing thickness at the constant flapping frequency 5 Hz. The experimental conditions are shown in Table.1. In this study, the value of $C_L$ is calculated as follows.

$$C_L = \frac{2L}{pU^2S} \quad (1)$$

### Table 1 Experimental conditions of fluid force measurement

<table>
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<tr>
<th>$F_4$ (degree)</th>
<th>0</th>
<th>10</th>
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<tr>
<td>$t$ (mm)</td>
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<tr>
<td>0.2</td>
<td>×</td>
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<td>Case 4 (---)</td>
<td>Case 7 (---)</td>
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<td>Case 5 (—)</td>
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<tr>
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<td>×</td>
<td>×</td>
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<td>Case 6 (—)</td>
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Here, $L^*$ is the time averaged value of lift for 20 seconds of sampling time in fluid force measurement. $\rho$ is fluid density. Same as $C_l$, the value of $C_D$ is also calculated. From this figure, it is confirmed that the lift coefficients in case4 ($FA$:20 degrees, $t$:0.2mm) and case5 ($FA$:20 degrees, $t$:0.5mm) are larger than those of case1(fixed wing) over the whole angles of attack range measured. Fig.7 shows the lift temporal variation in case1, case4 and case5 at $\alpha=20$ degrees and the temporal flapping angle $\theta$ which was calculated based on the encoder output signal. In this figure, green solid circles show the positions of maximum and minimum lift in first period of case4 and case5. From this figure, it is confirmed that the lift fluctuating range of flapping wing is larger than fixed wing, additionally the lift values always show positive in case4. Further, the lift tends to increase in the flapping angle range from the middle point to the bottom dead point in down stroke. In comparing case4 with case5 in terms of the waveform, the maximum lift value is obtained at the bottom dead point in down stroke, and the minimum lift value is obtained at the top dead point in upstroke respectively in case5. On the other hand, the phase angle of the lift curve in case4 is delayed by 45 degrees which is the averaged value in five periods, compared to case5. This feature is thought to be due to a flexibility of the wing. That is, it is possible to be a torsional deformation near the wing tip.

Fig.8 shows the lift-drag ratio curves corresponding to Fig.6. From these curves, it is stated that the values of case4 are large over the whole angles of attack range in comparison with other cases. The maximum lift drag ratio in case4 is 1.77 times the fixed wing. While, the values of case5 are not so large because of the large drag.

### 4.2 PIV measurement

We found that the $C_l$ value increased with attack angle till attack angle of 15 degrees and become nearly constant while the thinner plate of flapping amplitude of 20 degrees gives the peak of lift-drag ratio at attack angle of 5 degrees.

So we focus only the velocity field around the flapping wing in optimal conditions of the fluid force measurement.

The experimental conditions of PIV are shown in Table.2.

#### 4.2.1 Discrete PIV

In this study, this Discrete PIV trigger measurement is performed when the elliptical wing is just passing through the midpoint of the flapping amplitude ($\theta \geq 0$ degree) for 40 seconds.

Firstly, we demonstrate the flapping effect showing good aerodynamic characteristics of lift-drag ratio at angle of attack $\alpha=5$ degrees. Fig.9 shows the PIV result for the fixed wing in measurement No.1 as shown in Table.2.

Here, $\theta$ is the time averaged value of lift for 20 seconds. From this figure, it is confirmed that the lift coefficients in case4 ($FA$:20 degrees, $t$:0.2mm) and case5 ($FA$:20 degrees, $t$:0.5mm) are larger than those of case1(fixed wing) over the whole angles of attack range measured. Fig.7 shows the lift temporal variation in case1, case4 and case5 at $\alpha=20$ degrees and the temporal flapping angle $\theta$ which was calculated based on the encoder output signal. In this figure, green solid circles show the positions of maximum and minimum lift in first period of case4 and case5. From this figure, it is confirmed that the lift fluctuating range of flapping wing is larger than fixed wing, additionally the lift values always show positive in case4. Further, the lift tends to increase in the flapping angle range from the middle point to the bottom dead point in down stroke. In comparing case4 with case5 in terms of the waveform, the maximum lift value is obtained at the bottom dead point in down stroke, and the minimum lift value is obtained at the top dead point in upstroke respectively in case5. On the other hand, the phase angle of the lift curve in case4 is delayed by 45 degrees which is the averaged value in five periods, compared to case5. This feature is thought to be due to a flexibility of the wing. That is, it is possible to be a torsional deformation near the wing tip.

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### Table 2 Measurement conditions of PIV analysis

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<td>20</td>
<td>20</td>
<td>0.5</td>
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From this figure, although the small bulge of the velocity vectors like bubble near the upper surface is observed, the boundary layer flow almost dominates along the upper surface. Fig.10 shows the PIV result in down stroke for measurement No.2 showing maximum lift-drag ratio. As can be seen in this figure, the flow separates at the leading edge vortex V2 being formed by maximizing lift coefficient are shown in Fig.13 and Fig.14. From this figure, it is confirmed that the lift coefficients in case4 ($FA$:20 degrees, $t$:0.2mm) and case5 ($FA$:20 degrees, $t$:0.5mm) are larger than those of case1(fixed wing) over the whole angles of attack range measured. Fig.7 shows the lift temporal variation in case1, case4 and case5 at $\alpha=20$ degrees and the temporal flapping angle $\theta$ which was calculated based on the encoder output signal. In this figure, green solid circles show the positions of maximum and minimum lift in first period of case4 and case5. From this figure, it is confirmed that the lift fluctuating range of flapping wing is larger than fixed wing, additionally the lift values always show positive in case4. Further, the lift tends to increase in the flapping angle range from the middle point to the bottom dead point in down stroke. In comparing case4 with case5 in terms of the waveform, the maximum lift value is obtained at the bottom dead point in down stroke, and the minimum lift value is obtained at the top dead point in upstroke respectively in case5. On the other hand, the phase angle of the lift curve in case4 is delayed by 45 degrees which is the averaged value in five periods, compared to case5. This feature is thought to be due to a flexibility of the wing. That is, it is possible to be a torsional deformation near the wing tip.

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edge and then reattaches on the upper surface at \( x/L = 0.75 \), where \( x \) is the chord wise distance from the leading edge, \( L \) is the wing chord length of laser irradiation position. As a result of these behaviors of fluid particles, the relatively large leading edge vortex \( V_1 \) is formed possibly because the relative attack angle is greater than the mean attack angle due to the down stroke motion. These reattachment and reversed flows as shown in Fig.10 always appear on the upper surface in down stroke for this measurement case No.2. Fig.11 shows the PIV result in upstroke for measurement No.2. From this figure, it can be stated that the separation bubble is suppressed and the flow field is almost the same as the measurement No.1 for fixed wing.

Secondly, we demonstrate the flapping effect showing good aerodynamic characteris tics of lift coefficient at angle of attack \( \alpha = 20 \) degrees. Fig.12 shows the PIV result for the fixed wing in measurement No.3. From this result, the leading edge separated flow does not reattach to the upper surface of the wing, that is, distinct leading edge vortex is not confirmed. The flow velocity just near the upper surface at mid span of the wing is 3 m/s or less. All of the PIV results for 40 seconds are the same as the result of Fig.12. Therefore, there is a steady wake above the upper surface. The separated vortices patterns obtained from the PIV results in measurement No.4 showing maximizing lift coefficient are shown in Fig.13 and Fig.14. Seeing Fig.13, the trailing edge vortex \( V_2 \) being formed by the flow from the lower surface to roll up toward the upper surface of the wing is observed. Further, the leading edge vortex \( V_1 \) is formed as to be attracted to \( V_2 \). From another velocity pattern in Fig.14, the growth of \( V_1 \) is identified, and then this vortex moves downstream as wake. As these results, large scale of leading edge vortex near the upper surface in the down stroke often has local minimum of pressure and the upper surface in the stroke acts as back pressure side so it contributes to increase in lift force. Further, we challenge to perform the fluid force measurement at the same timing as PIV measurement by means of the rotary encoder signal from flapping motion as shown in Fig.7. From this figure, it is confirmed that the waveform of case4 is more gradual compared to case5. This finding indicates the leading edge vortex exist near the upper surface of the wing for longer duration.

Fig.15 shows the vorticity distributions at measurement No.3 and No.4. It is seen that two kinds of small regions of positive or negative vorticity values exist alongside at the upstream of the wing. These vorticity distributions are attributable to the mask processing for the regions at the lower part of the wing where the laser light sheet could
not be irradiated, and for the regions of extremely strong scattering light of the laser in this PIV analysis. From these figures, it is found that the high vorticity region in appropriate flapping condition approaches the body surface relative to the fixed wing. This finding shows the existence of stable leading edge vortex having its axis in the span wise direction.

4.2.2 Continuous PIV

In this study, this continuous PIV trigger measurement is performed when the elliptical wing is just passing through the midpoint of the flapping amplitude ($\theta_0$=0 degree) at the same timing as discrete PIV technique. This continuous PIV analysis can clarify temporal change of separated vortex behavior and enables to consider about the interaction of each separated vortex. In this measurement, we get continuous PIV image of 30 frames at one trigger signal with recording rate of 1000 fps.

Firstly, Fig.16 shows the results of continuous PIV in down stoke for measurement No.2 showing the maximum lift-drag ratio at $\alpha$=5 degrees. From these continuous results, the leading edge vortex which can be confirmed in previous discrete PIV measurement grows with time. According to this observation, it is considered that strong reattachment flow exist steadily.

Secondly, Fig.17 shows the results of continuous PIV in down stoke for measurement No.4 showing the maximizing lift coefficient at $\alpha$=20 degrees. From this result, trailing edge vortex $V_4$ and leading edge vortex $V_5$ can be confirmed. Moreover, these continuous results show clearly the state of vortex $V_5$ to form near the upper surface as to be attracted to vortex $V_4$.

5. Conclusion

In this study, the development in order to improve aerodynamic characteristics of a flapping wing was performed using fluid force measurement and PIV analysis. The following conclusions were derived from the results and discussion.

1. Flapping motion with the optimal flapping amplitude such as 20 degrees and the wing thickness such as 0.2mm is really effectual to enhance aerodynamic characteristics.

2. The influence of flapping motion on fluid dynamical phenomena such as the time histories of the layout of the separated vortices and the position of the leading edge vortex core can be evaluated quantitatively according to precisely-triggered PIV measurement.

3. The key fluid dynamical phenomenon to get maximum lift-drag ratio is the leading edge vortex to approach the upper surface of the flapping wing in down stroke motion.

4. The interaction between leading edge vortex and trailing edge vortex in down stroke motion leads to improved aerodynamic characteristics such as maximizing lift coefficient.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>AR</td>
<td>aspect ratio</td>
</tr>
<tr>
<td>b</td>
<td>half of wing span [mm]</td>
</tr>
<tr>
<td>c</td>
<td>chord length of wing root [mm]</td>
</tr>
<tr>
<td>$C_D$</td>
<td>drag coefficient</td>
</tr>
<tr>
<td>$C_L$</td>
<td>lift coefficient</td>
</tr>
<tr>
<td>$C_L/C_D$</td>
<td>lift-drag ratio</td>
</tr>
<tr>
<td>$D^*$</td>
<td>time averaged value of drag</td>
</tr>
<tr>
<td>$FA$</td>
<td>flapping amplitude [degree]</td>
</tr>
<tr>
<td>L</td>
<td>wing chord length of laser irradiation position [mm]</td>
</tr>
<tr>
<td>$L^*$</td>
<td>time averaged value of lift [N]</td>
</tr>
<tr>
<td>S</td>
<td>wing platform area [mm$^2$]</td>
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the span wise direction.
existence of stable leading edge vortex having its axis in surface relative to the fixed wing. This finding shows the appropriate flapping condition approaches the body these figures, it is found that the high vorticity region in scattering light of the laser in this PIV analysis. From not be irradiated, and for the regions of extremely strong results, the leading edge vortex which can be confirmed in lift-drag ratio at α = 5 degrees. From these continuous results and discussion.

4. Conclusion
(1) Flapping motion with the optimal flapping amplitude
(2) The influence of flapping motion on fluid dynamical phenomena such as 20 degrees and the wing thickness such as 0.2mm is really effectual to enhance aerodynamic characteristics such as lift-drag ratio in down stroke motion leads to trailing edge vortex in down stroke motion.
(3) The key fluid dynamical phenomenon to get maximum
(4) The interaction between leading edge vortex and reattachment flow exist steadily.

Acknowledgement
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References