
Abstract:
This paper has completed the study of aerodynamic properties and flow structures of two wings in tandem arrangement, including the experiments of force and velocity measurements and analysis to investigate the flow structures and their development of trailing vortices. The wingtip vortices generated from the front wing is investigated from the streamwise velocity ratio contours and turbulent intensity. The results show that the tip vortex dissipates and spreads outside after passing the position of X/C=5. According to the results of the aerodynamic performance and coherent flow structure of the following wing, the impingement of tip vortices or wake generated from the front wing indeed drastically affect the following wing. The following wing shows a thin-airfoil stall without the obvious flow interaction from the front wing. However, the lift coefficient and drag coefficients were affected by the flow interaction from the upstream.

Keywords: Tandem arrangement, Trailing vortices, Turbulent intensity, Tip vortex dissipates, Flow Interaction

1. Introduction
The behaviors of wingtip vortex and corresponding wake flow structure behind the formation of finite wings or have been studied for recent decades. When the wing generates lift force by the pressure gradient, the air flows will spread out around the wingtips from the lower surface to the upper surface of wing with a circular motion which are the so-called tip vortices [1] and the flow structure of downwash and upwash regions will be formed between these pair of vortices at wake flow region. As the wingtip vortices dissipate slowly and linger in the atmosphere rather than merging, this flow structure is named wake turbulence which influences the flight stability of following aircraft and is a hazard to the air traffic safety. Observing the direction of V-formation flight of birds, the aerodynamic efficiency of the following birds can be improved due to the existence of the wingtip and trailing vortices produced from the leading bird [2]. Therefore, for the application of unmanned aerial vehicle (UAV) design, the endurance time and distance can be extended if we can find the proper position between each UAV in flight formation. For the references on the formation flight studies, Moelyadi, and Muhammad [3] used numerical method to simulate the effect of leader’s position on aerodynamic performance, and Ding and Hsiao [4] used fuzzy logic control to keep two UAVs flying in formation. Nevertheless, most of the studies about formation flight of UAV were done by the control law designs or simulation methods, few of the studies are conducted by the experimental technologies or verifications. Hence, the paper uses the force and velocity measurement methods to study the aerodynamic and flow properties of proceeding wing both with and without the influence of wake and vortices generated from the front wing, which use two low aspect ratios (AR) rectangular wings in the open type of low-speed wind tunnel at the critical mode of Reynolds numbers (Re). The velocity measurement is conducted by the hot-wire anemometer for study the velocity properties, and determines the response of the following wing with and without the effect of trailing vortices generated from the front wing. In

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conclusion, it is expected to determine how severe the vortex can affect the attitude of the following wing and find an appropriate position where the aerodynamic performance of the following wing can be improved.

2. Experimental Apparatus

The experimental facilities include a subsonic low speed wind tunnel, force measurement and velocity measurement system, calibration processes and uncertainty analysis which include the experimental results of forces, free stream velocity, streamwise (X) and transverse (Z) direction of flow velocities which will be introduced as follows.

2.1 Low speed wind tunnel

All the experiments are performed in a horizontal, open-type subsonic low speed wind tunnel at National Cheng Kung University as illustrated in Fig.1 (a). The inlet of tunnel consists of five fine mesh anti-turbulence screens and its contraction ratio is 9 to 1 with the test section area of 4400mm (length) × 1200mm (width) × 914mm (height). The free stream velocity in test section can be varied between 4m/s and 20m/s, where the corresponding turbulence intensity following the increase of free stream velocity is show in Fig.1 (b). The turbulence intensity is less than 0.2% for free stream velocity greater than 6m/s and the highest turbulence level is 0.45% attainable free stream velocity.

2.2 Force and moment measurement system

The force and moment measurement system shown in Fig. 2 consists of a six-component strain-gage type force balance, Wave-book 512 Analog/Digital (A/D) converter, and AOA servo device to measure the forces and moments. The fully-limited loading ranges of the force balance are 5 kg of lift force in Z direction, 3 kg of drag force in X direction, and 0.025 kg-m of pitch moment. The output voltages of each component after amplification were transmitted to a computer through the A/D converter, and the digitized data was converted into the real force/moment data via the linear coupling matrix shown in Eq. (1). The values of “ΔV” represent the voltage differences measured by A/D converter, while the elements of the 6×6 transition matrix are obtained from the force/moment calibration system. Therefore, the desired forces (Fx, Fy, Fz) and moment (Mx, My, Mz) can be easily calculated.

Fig.1 Low speed wind tunnel and variation of turbulence intensity with free stream velocity
\[
\begin{bmatrix}
F_x \\
F_y \\
F_z \\
M_x \\
M_y \\
M_z \\
\end{bmatrix}
= 
\begin{bmatrix}
a_{11} & \cdots & a_{16} \\
\vdots & \ddots & \vdots \\
a_{61} & \cdots & a_{66} \\
\end{bmatrix}
\begin{bmatrix}
\Delta V_1 \\
\Delta V_2 \\
\Delta V_3 \\
\Delta V_4 \\
\Delta V_5 \\
\Delta V_6 \\
\end{bmatrix}
\]

(1)

2.3 Velocity measurement system

The velocity measurement system shown in Fig. 3 consists of constant temperature anemometer, cross-type hotwire probe, Analog/Digital (A/D) converter, and three-axis traversing mechanism to measure the span-wise and transverse direction of flow velocity components. The platinum-plated tungsten wire is used as the sensing element, and the initial resistivity of each wire is near 5 Ω. The King’s Law is applied to the calibration of hotwire probe [5] to correlate the relation of velocity (U), normal to the wire, and the output voltage (E) of anemometer which is shown in Eq. (2)

\[
E = A + B U^{0.5}
\]

(2)

The sampling frequency in the present study is between 1024~2048Hz with 4096~16384 points of samples. The long time average technique is used to calculate mean and fluctuation velocity. Each velocity component is defined in Eq. (3) and Eq. (4), respectively.

\[
U_{mean} = \frac{1}{N} \sum_{i} U
\]

(3)

\[
U_{rms} = \sqrt{\frac{1}{N-1} \sum_{i} (U - \bar{U})^2}
\]

(4)

For the velocity measurement, the maximum uncertainty at each point of velocity component is analyzed to be less than 3% with 4096~16384 points of samples.
2.4 Test model

Two models illustrated in Fig. 4 are used in this study for the front wing and following wing, respectively. The front wing, whose chord length is 15cm with aspect ratio (AR) of 2, is a half-span model side-mounted on the tunnel wall, while the following wing is a full-span model with the chord length of 10cm and AR of 6. Both models use the same airfoil of NACA 0012. Both models are made of wood and fiber of glass with the platform of rectangle.

![Fig.4 Test models](image)

2.5 Uncertainty analysis of experimental data

A statistical analysis scheme, called Student’s t distribution, is employed for the experimental data’s uncertainty analysis [6]. It was first used by Gosset in 1908 who supposed a random sample of number “n” with mean “μ”, sample mean “x̄” and standard deviation “σ”, shown in Eq. (5). According to the characteristics of the Student’s “t” distribution, the larger the degree of freedom, the closer the t-density to the normal density will be. Then the experimental data quantity obtained can be warranted.

\[ t = \frac{x - \mu}{\sigma / \sqrt{n}} \]  

(5)

The main purpose of wind tunnel experiments is to measurement the stationary aerodynamic force and moment for a combination of controlling variables such as \( Re \) or \( AOA \). For the variables,
the mean value of recorded data ($\bar{x}$) and the uncertainty ($\Delta \bar{x}$) of force and moment in three axes are computed with Eq. (6).

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$  

(6)

In this study, the significant level of accuracy is considered to be a 95% confidence interval. For the sampling frequency of A/D converter controlled at 1000 Hz in the experiment, the random variable “$t_{n-1}$” is the Student’s “$t$” distribution with n-1 degrees of freedom. Eq. (7) is used to compute the confidence interval when the value of “$t$” is approaching 1.96. Fig. 5 illustrates one of uncertainty analysis of experimental results of lift and drag coefficients at $Re=1.0\times10^5$. For the results, the maximum value at each point of Fig 5 is less than 3% with 16384 of numbers of samples.

$$\Delta \bar{x} = 1.96 \frac{\sigma}{\sqrt{n}}$$  

(7)

Fig. 5 Uncertainty analysis of lift coefficient of following wing with $AR=6.0$ and $Re=1.0\times10^5$

2.6 Coordinate of force and velocity measurement

For the measurement of forces and moments of the following wing, the positions of following wing related to the front wing need to be determined first. In $x$-direction, the horizontal distance between the front wing and the following wing shown in Fig. 6(a) is 30cm ($X/C=2$), 45cm ($X/C=3$) and 60cm ($X/C=4$), respectively. In $y$-direction, the two cases which the core of wingtip vortex pass the different position of the following wing shown in Fig. 6(b) are determined to simulate different tip spacing of formation, and they are the midline (case 1) and quarter line (case 2) of the following wing, respectively. In $z$-direction, three different positions are determined to investigate the effect of downwash and upwash to the following wing at different positions. The vertical distance between the front wing and following wing is 3cm above the trailing edge ($Z/C=0.2$), 0cm ($Z/C=0$) and 3cm($X/C=-0.2$) below the trailing edge of the front wing shown in Fig. 6(c). For the measurement of mean streamwise velocity and fluctuation velocity in near-wake region of following wing, the measurement areas are located at X-Z plane with variation of X between 0.1C (C represents the chord length of the following wing) and 3.0C and Z between -0.5C and 0.5C shown in Fig.6(d).
Fig. 6 Different position of the following wing in x, y, z direction and the velocity measurement region of following wing
3. Experimental Result and Discussion

The measurement of flow structure contains the flow development of front wing, streamwise velocity profile and turbulent intensity of the following wing at wake flow region and the aerodynamic properties with variation of lift and drag coefficient will be described as follow.

3.1 Flow Development of Mean Velocity

The streamwise mean velocity and velocity fluctuation in the wake region along streamwise location from the front wing is illustrated in Fig. 7. The free stream velocity is 9.74 m/s and $AOA=10^\circ$. At the trailing edge ($X/C=0$), the value of contour line decreases from the outer to the inner one apparently, and the core of wingtip vortex is clear. In the section of $X/C=5$, the core obviously dissipate and diffuse externally as the flow develops along downstream. Therefore, the wingtip vortex core can sustain from the cross-section near the trailing-edge to the cross-section at $X/C=5$, and then the wingtip vortex dissipates. However, the wingtip vortex structure is more obvious either on the upper region or the lower region of the front wing and the process of spreading and descending are also more obvious. Two circular regions are formed on the upper and lower region, and the lower circular region is wider because the $AOA$ of front wing is positive. From turbulence intensity contours at each cross-section, the wingtip vortex core is clearer to be observed. Besides, the decelerated region descends from trailing edge of front wing to the cross-section at $X/C=5$ due to the downwash effect. The wingtip vortex development along

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![Fig. 7 The development of wingtip vortex structure](image-url)
downstream will reduce a low-pressure region and increase velocity in this region. Therefore, it is accelerated by low pressure region attraction. The flow separation phenomenon is similar to a 2-D flow field near the wing root, and the flow separation will induce the tip-vortex effect near the wingtip. Therefore, the wake flow velocity distribution keeps basic 2-D flow characteristics.

3.2 The interaction of flow structures
The flow passing through the upper surface of wing creates a decelerated range which is a protruding in the velocity profile, and then the velocity ratio returns to the original value which is measured at the lowest point on the lower region of following wing. Therefore, the influence of flow structures of following wing with the flow interaction from the front wing can be observed. To investigate the influence of flow interaction, the AOA of the front wing is fixed at 10° (not stall) in the present study. The freestream velocity is 9.74m/s, and the Re is in the critical modes of 1.0×10^5. For the streamwise velocity profile at section near the trailing edge of the following wing with the front wing at AOA=10° shown in Fig. 8, the influence of flow interaction is more obvious due to the looseness of the flow structure on the upper region of the following wing. Meanwhile, the streamwise velocity profile at the position where the following wing is below the front wing (Z/C=-0.2) is more apparent than the position where the following wing is above the front wing (Z/C=0.2) in near-wake region due to the downwash effect which cause the wake flow passing through the following wing, and it means that the level of flow interaction is in connected with the relative position in z-direction of the front wing and the following wing.

For the turbulent intensity in streamwise direction, the influence of flow interaction is more apparent than the streamwise velocity profile of the following wing as the front wing is at AOA=10°. The influence of flow interaction sustains to the farthest section (X/C=3.0) to tell the level of flow interaction for the following wing at different positions in z-direction. From the experimental results, the position of the following wing below the front wing (Z/C=-0.2) suffers more obvious flow interaction than the position of the following wing above the front wing (Z/C=0.2). The wake flow descends because of the downwash effect generated from the front wing, so the influence of

![Fig.8 The flow development for following wing when the front wing is at AOA=10°](image-url)
flow interaction passing through the position where the following wing is below the front wing is more than the position where the following wing is above the front wing and cause an apparent difference on both streamwise velocity profile and turbulent intensity.

3.3 Measurement of lift and drag Coefficient

In the study of force measurement, the front wing, which is called vortex generation wing is fixed at $AOA = 10^\circ$. The freestream velocity is 9.74m/s, the characteristic length is 15cm (the chord length of the front wing) to keep the $Re$ fixed at $1.0 \times 10^5$. To study the aerodynamic properties for the following wing with the influence of the vortex generation wing (front wing), the variation of lift and drag at each position of the following wing is calculated. Also, the $\Delta C_L$ and $\Delta C_D$ defined from Eq. 8 and Eq. 9 are used as symbols,

$$\Delta C_L = C_{L_{measured}} - C_{L_{original}}$$ (8)

$$\Delta C_D = C_{D_{measured}} - C_{D_{original}}$$ (9)

where the $Original$ in subscript represents the measured result of the following wing without the flow interaction and the others represent the measured result of the following wing with the flow interaction. The curves of lift coefficient of the following wing with the flow interaction in free flow field are illustrated in Fig. 9, and the dotted line represents the theoretical value of lifting.

![Graph](image)

(a) The core of vortex passing through the center line of following wing

![Graph](image)

(b) The core of vortex passing through the quarter line of following wing

Fig.9 The lift coefficient curves with AOA=$10^\circ$ of front wing at $XC=2$, $Re=1.0 \times 10^5$
line theory. For the lift coefficient curve of the following wing in free flow field, the first nonlinear region where the values are smaller than the theoretical values is from \( AOA = -10^\circ \) to \( AOA = -1^\circ \); the second nonlinear region where the values are larger than theoretical calculation is from \( AOA = 0^\circ \) to \( AOA = 2^\circ \). After the AOA of the following wing is larger than 3\(^\circ\), the values of lift coefficient are smaller than the theoretical values. At last, the curve begins to level at \( AOA = 7^\circ \), and then the curve would descend and ascend when the AOA of the following wing continues to increase. From the result, the following wing suffers a leading edge separation-long bubble type stall which is a gradual stalling with laminar separation bubble and flow reattachment [7, 8].

The curves of the drag coefficient are illustrated in Fig. 10. For the drag coefficient curve of the following wing in free flow field, the smallest value is at \( AOA = 2^\circ \), there is a small increase of slope between \( AOA = 6^\circ \) and \( AOA = 7^\circ \), and then the drag coefficient continues to increase as the AOA increases. The trend of drag coefficients is similar as the original curve no matter which position of the following wing is located. However, the values of drag coefficients of the following wing with flow interaction seem to have regularity. The \( \Delta C_D \) of the following wing above the front wing (\( Z/C = 0.2 \)) is the highest at the section of \( XC = 2 \). In the present study, the highest value of \( \Delta C_D \) is at the \( AOA = 7^\circ \), and it is matched the leveled point of AOA on the lift coefficient curves. However, there is an enormous peak of \( \Delta C_D \) at \( AOA = 7^\circ \) and it indicates that the drag increases more dramatically when the following wing is near stall.

(a) The core of vortex passing through the center line of following wing

(b) The core of vortex passing through the quarter line of following wing

Fig. 10 The drag coefficient curves with AOA=10\(^\circ\) of front wing at \( X/C = 2 \), \( Re = 1.0 \times 10^5 \)
In conclusion, the results demonstrate that the additional lift can be generated due to the upwash as the following UAV flies behind the lead UAV from the section at X/C=2 to X/C=4 and the vertical distance is 15cm below (Z/C=0.2) the lead UAV. As well, the drag is increased when the following UAV flies right astern the lead UAV from the section at X/C=2. However, the influence of following wing from wingtip vortices may be different after the changes of attitude or tip spacing. As mentioned before, the V-formation of migrating birds are changing during the flight, and it indicates the birds can find the proper position to increase the aerodynamic efficiency and saving the biological energy themselves. Therefore, the position with better aerodynamic properties of the following UAV needs to be corrected along with the change of attitude of the lead UAV.

4. Conclusion

The wake flow characteristics of the front wing and the aerodynamic properties of the following wing have been experimentally investigated by conducting the forces and velocities measurements with low AR wings at critical Re. The flow is forced to circulate around the wingtips from the high-pressure region just underneath the wingtips to the low-pressure region on the upper surface of the wing. Furthermore, the structure of wingtip vortex sustains to the section of X/C=5 and the core begins to descend and dissipate externally. From the studies of the flow characteristics of the following wing with the influence of the front wing, the streamwise velocity profile and turbulent intensity profile are affected dramatically near the trailing edge of the following wing, and the influence is getting slighter as the flow goes downstream. As the following wing located in the range of wingtip vortex, the lift of the following wing increases higher than the value in the free stream condition. For the discussion on the drag coefficient, the curves of the following wing at location of Z/C= -0.2 and Z/C= 0 are closed to the result without the flow interaction. However, the following wing is at location of Z/C= 0.2 and X/C= 2, the drag coefficient curve is higher. All of the experimental results indicate that the aerodynamic performance of the following wing is drastically affected due to the impingement of the wingtip vortices or wake from the front wing. For the UAV formation flight issue, the tip spacing of formation and relative position in three directions make difference on their aerodynamic properties. From the results, the lift can increase under the flow interaction and the drag can either decrease or remain the same. Therefore, the positions with better aerodynamic performance of the following wing are determined. However, such positions can change as the leading wing is changed. Observing the flight formation of birds, the following birds have to adjust the relative position to the leading bird, so the formation doesn’t remain constant. Therefore, the relative position of the following UAV needs to be moved as the attitude of lead UAV changes.

Nomenclature

\[ u' \] Instantaneous streamwise velocity [m/s]

\[ U_\infty \] Free stream velocity [m/s]

\[ \alpha \] Angle of attack [Degree]

\[ \Omega \] Resistance [Ohm]

Subscripts

\[ AOA \] Angle of attack

\[ AR \] Aspect ratio

\[ E \] Output voltage

\[ n \] Random sample of number

\[ N \] Number of sample

\[ Re \] Reynolds numbers

\[ UAV \] Unmanned aerial vehicle
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Reference