An experimental study on the aerodynamic performance of flexible tandem wings

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**AN EXPERIMENTAL STUDY ON THE AERODYNAMIC
PERFORMANCE OF FLEXIBLE TANDEM WINGS**

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AN EXPERIMENTAL STUDY ON THE AERODYNAMIC PERFORMANCE OF FLEXIBLE TANDEM WINGS

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Abstract

The real dragonflies have the features of both flexibility and tandem-wing configuration, which have been widely studied and proven to account much for the great flight capabilities of dragonflies. However, these two features were usually concerned separately. The present work aims to investigate the combined effect of flexibility and tandem configuration by studying the aerodynamic performance of flexible tandem wings. The wing models undergoing combined pitching/plunging motion were studied in tandem configurations with phase differences between forewing and hindwing of 0° , 90° and 180° , as well as in a single configuration. Three sets of dragonfly-like flexible tandem wing models termed Wing I, Wing II and Wing III, which were progressively less flexible, and a set of rigid tandem wings were used for the investigation.

First, to offer a more comprehensive understanding of the aerodynamic performance of tandem wings, force and phase-locked particle image velocimetry (PIV) measurements were carried out to investigate the forewing-hindwing interactions associated with the rigid tandem wings in both hovering ($Re_{\overline{U}_p} = \frac{\overline{U}_p \overline{C}_{fore}}{\nu} = 4,544$) and forward ($Re_{U_\infty} = \frac{U_\infty \overline{C}_{fore}}{\nu} = 3,873$, $St = \frac{2fh_0}{U_\infty} = 0.6$) flights. The phase differences affected the force peaks significantly. Moreover, phase lags between force traces at different phase differences were also observed. 0° and 90° contributed to the highest horizontal force in hovering and forward flights, respectively. In current study, the tandem rigid wings outperformed the single wing in certain cases. This result is contrary to most of previous study,

which showed that the tandem rigid wings performed worse than the single rigid wing. Comparing the current study with previous studies, the differences in flow parameters such as Re and St and in wing motions such as plunging amplitude, were shown to have crucial effect on the aerodynamic performance significantly. This implies the possibility that the better performance can be achieved by the tandem wings as compared to single wing by modifying the flow parameters and wing kinematics. By analyzing the velocity and vorticity fields around the wing models in tandem-wing and single-wing configurations, the mechanisms of how the interactions between fore- and hindwing affects the horizontal force generation on the forewing and hindwing were revealed. For the forewings, the hindwings at different phase differences modified the direction and strength of forewing's downwash flows, thus the strengths of TEVs on the forewings. For the hindwings, the forewings induced different downwash flows to affect both the strength and location of LEVs on the hindwings. The modified LEVs then further affected the strengths of TEVs. The analysis on the location of LEV on the hindwing was discussed for the first time in current study. Comparing the hovering and forward flights, the incoming flow enhanced the effect of forewings on the hindwings by shifting the LEVs and TEVs of forewings backward. Furthermore, incoming flow in forward flight also directly modified the direction of the downwash flow induced by the forewing, which led to the change of its effect on the hindwing.

The aerodynamic performance of flexible tandem wings were studied in hovering flight ($Re_{\overline{U}_P} = 4,544$) and two forward flights ($St = 0.6$ and 0.3) by performing force, 2D deformation and phase-locked PIV measurements. The results showed that both the flexibility and phase difference have significant effects on the aerodynamic performances. In both hovering and forward flights at $St=0.6$, the tandem Wing III models outperformed the other wing models in terms of

total average horizontal force coefficient and efficiency at all phase differences studied. In forward flight at $St = 0.3$, it was the tandem Wing III, rigid wings and Wing II models that performed the best at 0° , 90° and 180° phase difference, respectively. For the tandem Wing III model, it was 0° that led to the largest average horizontal force in both hovering and forward flights at $St = 0.6$, while 90° in the forward flight at $St = 0.3$. Different peak values, phase lags, and secondary peaks on the force traces are the main reasons causing the differences in the average horizontal force coefficients of different wing models. The results of 2D deformation and phase-locked PIV measurements showed that the spanwise bending deformation of Wing III was able to contribute to the horizontal force, by inducing LEVs closer to the Wing III models in both hovering and forward flights, and by inducing a higher-velocity region in forward flight.

Finally, the force dynamics of the flexible tandem wings in hovering flight ($Re_{\overline{U}_p} = 4,544$) were further investigated by carrying out 3D deformation and time-resolved PIV measurements. In both single-wing and tandem-wing cases, significant bending deformation was found to cause the lags of wing locations in plunging direction between the flexible and rigid wings, i.e. the flexible wing was always behind the rigid wing in plunging direction. In single-wing configuration, the Wing III model with appropriate flexibility produced stronger LEVs as compared with the rigid wing due to the lags. Moreover, the shedding of LEV on the Wing III model was restrained slightly by the lags. These effects resulted in different lift dynamics of Wing III and rigid wing in single-wing configuration. In tandem-wing configurations, the flexibility not only caused the lags but also the modifications in the relative positions of forewing and hindwing. The lags and modified relative positions affected the interactions of the tandem wings, and thus the lift dynamics on the hindwings mainly in two ways: 1) The flows induced by the fore- Wing III and rigid wing showed different

effects on the strength and location of LEVs and TEVs on the hindwings; 2) The modifications in the relative positions resulted in quite different interactions of LEV on the hindwing and TEV on the forewing for the tandem Wing III and rigid wings, especially in 90° and 180° -phased tandem-wing configurations.

In summary, the flexible tandem wings showed great advantages in force generations and force efficiency, which offered a new development direction for the MAV design. Moreover, the flexible tandem wings also show great potential in flight control by modifying the force dynamics with wing deformations. Last but not least, the present work provides experimental results to the future numerical work for validation.

To My Beloved Parents.

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List of Abbreviations

DLT	Direct linear transformation
LEV	Leading-edge vortex
MAV	Micro air vehicle
PIV	Particle image velocimetry
TEV	Trailing-edge vortex
2D	Two-dimensional
3D	Three-dimensional

List of Symbols

English

B_r	bias error of force measurements
C_{fore_m}	chord width of forewing at the middle of the wing span
$\overline{C}_{fore}$	mean chord width of forewing
C_{hind_m}	chord width of hindwing at the middle of the wing span
C_H	horizontal force coefficient
C_P	power coefficient
C_V	vertical force coefficient
EI_{chord}	chordwise flexural stiffness
EI_{span}	spanwise flexural stiffness
f	frequency of plunging motion
F_C	force parallel to the wing surface
F_H	force in horizontal direction
$\overline{F}_H$	average horizontal force
F_N	force normal to the wing surface
F_V	force in vertical direction
h_0	amplitude of plunging motion
h_{fore}	plunging motion position for forewing
h_{hind}	plunging motion position for hindwing
$\dot{h}$	plunging velocity
J	advance ratio

k	reduced frequency
K	confidence coefficient
L	wing length
L_{fore}	wing span length of forewing
L_{hind}	wing span length of hindwing
L_{chord}	distance between leading edge and load point in chordwise direction
L_{span}	distance between wing root and load point in spanwise direction
M	1/4-chord pitching moment
N	number of cycles
n	frequency of flapping motion
P	power consumed
P_r	precision error of force measurement
Re	Reynolds number
Re_{U_∞}	Reynolds number based on the velocity of incoming flow
Re_{U_w}	Reynolds number based on the velocity of wing motion
$Re_{\overline{U}_P}$	Reynolds number based on the mean plunging velocity
$R_{\lambda\omega}$	correlation between swirling strength and vorticity
S	area of wing model
S_d	sample standard deviation
St	Strouhal number
t	time
T	motion period
$\overline{U}_P$	mean plunging velocity
u	image coordinate in x direction
U_r	experimental uncertainty of force measurement
U_∞	velocity of incoming flow
v	image coordinate in y direction

$\vec{V}$ velocity vector

Greeks

α_0 amplitude of pitching motion

α_{fore} pitching motion position for forewing

α_{hind} pitching motion position for hindwing

$\dot{\alpha}$ pitching velocity

δ displacement caused by the point load for the measurements of chord-wise stiffness

ε efficiency in forward flight

$\bar{\rho}$ density ratio

ρ_f density of water

ρ_s density of wing models

λ_{ci} swirling strength

ν kinematic viscosity

ξ efficiency in hovering flight

ν Poisson's ratio

ω displacement caused by the point load for the measurements of span-wise stiffness

Π_1 effective stiffness

ω_z vorticity

Θ flapping stroke amplitude

Φ phase angle by which the pitching motion leads the plunging motion

Ψ phase angle by which the hindwing leads the forewing

Chapter 1

Introduction

1.1 Background

Micro air vehicles (MAVs) are a new type of aircraft of less than 15 centimeters in size which are useful for commercial, research, government, and military purposes. They can be applied in suspect facilities surveillance, weather forecast, crowd control and wildlife study, and so on. A lot of MAVs have been developed since 1990s ((Torres & Mueller, 2000), (Grasmeyer *et al.*, 2001), (Ifju *et al.*, 2002), (Sun *et al.*, 2005), (Karásek *et al.*, 2013)). Among all of the MAVs, insects-inspired MAVs have always been considered as the most important direction for MAVs' development due to their light weight and great aerodynamic performance at low Reynolds number (Re).

To investigate the factors accounting for the great performance of insects, many efforts have been made. So far, the aerodynamic performance of flapping wing flight has proved to outperform that of a the steady flight at low Reynolds number by many studies in last decades ((Dickinson *et al.*, 1999), (Sun & Tang, 2002), (Shyy *et al.*, 2010)). Furthermore, studies on the flexible wings of insects have shown that appropriate wing flexibility was able to contribute towards the aerodynamic performance of the insects. In recent years, a lot of numerical and experimental work was conducted to study the aerodynamic performance of four-wing insects. As typical four-wing insects, dragonflies were found to be able to control the phase difference between their forewing and hindwing to

hover, accelerate in almost any direction and manoeuvre precisely at high speed, thus showing a great advantage in maneuverability over other four-wing insects such as butterflies and bees ((Norberg, 1975), (Alexander, 1984), (Alexander, 1986), (Azuma & Watanabe, 1988), (Rüppell, 1989), (May, 1991), (Wakeling & Ellington, 1997b),(Thomas *et al.*, 2004)). The great aerodynamic performance of dragonflies makes them one of the most important insects to be studied for the development of insect-inspired MAVs.

1.2 Literature review

1.2.1 Aerodynamic performance of tandem wings

In Soms & Luttges (1985), lift measurements on a tethered dragonfly were carried out. Based on previous studies on the mechanisms of lift production in unsteady flapping flight motion, such as the study carried out by Weis-Fogh (1973), double peaks in lift were expected from the sum of four independent wings. However they found that single large lift peak occurred once in each stroke period which was different from double peaks. This result suggested that lift generation was dominated by the integrated interactions between wings rather than by the unsteady effects elicited independently by each of four wings. This paper revealed a novel mechanism of aerodynamic lift production, i.e. the interactions between tandem wings. However, the details of the interaction were not identified in their study.

Scharpf & Mueller (1992) studied two rigid wings (Wortmann FX63-137) in closely coupled tandem-wing configurations at $Re = 8.5 \times 10^4$ in forward flight motion. The experiments were carried out in a wind tunnel. Two wings were mounted vertically with a separation of 1.5 chord lengths between them. The angles-of-attack of two wings ranged from -15° to 20° with decalage angles of

0° and $\pm 10^\circ$. Although the lift and drag coefficients of all tandem-wing configurations were greater than the single-wing configuration, the lift to drag ratios varied. The greatest improvement was found to be an increase in lift to drag ratio of 77% which occurred at 5° and 10° angle-of-attack for the hindwing and forewing, respectively. The results indicated that benefits could be gained by using a tandem-wing configuration. But the conclusion was limited to steady flow conditions in this study. To investigate the aerodynamic interactions of two wings in unsteady flights, numerous numerical and experimental studies have been performed.

Lan & Sun (2001*b*) computationally studied two-dimensional (2D) tandem wings plunging forward and downward after an initial acceleration from rest in air with different horizontal and vertical spacings at $Re = 10^3$. The lift coefficients of forewing and hindwing were both found to be enhanced at the beginning stage. Each wing obtained a faster incoming flow due to the 'blockage' effect of the other wing, which mainly account for the enhancements in lift generations. At later times, the leading edge vortex (LEV) of hindwing diffused more and move downstream faster, as compared to the single-wing case, due to the existence of the trailing edge vortex (TEV) of forewing. So the lift coefficient of the hindwing decreased rapidly. The vertical spacing was found to contribute to the lift production on both forewing and hindwing when the hindwing was lower than forewing.

In their later study (Lan & Sun, 2001*a*), they added rotation to the plunging motion and studied the effects of phase differences at between the two wings in hovering flight at $Re = 10^3$. The phase differences, 0° , 90° and 180° , by which the hindwing led the forewing, were investigated. The results showed that 0° was the most favorable phase difference for the mean lift and resultant forces. At 90° , the highest mean thrust and the lowest resultant force were

generated. Comparing the single-wing and tandem-wing cases, they found that the forewing and hindwing interacted mainly in three ways: 1) Forewing moved towards the hindwing and thereby enhancing the incoming flow towards hindwing; 2) The effective angle of attack of one wing was changed by the induced flow produced by the vortices generated by the other wing; 3) The forewing TEV and the hindwing LEV interacted with each other and led to a change in the circulation around the hindwing. Sun & Lan (2004) then developed 3D models to numerically investigate the interactions between the forewing and hindwing with 180° phase difference in hovering flight at $Re = 1.35 \times 10^3$. Their study showed that the interaction was very weak and detrimental to the lift generation, as compared to the single-wing case. Comparing the 2D and 3D models, the 3D effect reduced the lift generation.

Wang & Sun (2005) numerically investigated the effect of phase differences, i.e. 0° , 60° , 90° and 180° , on the aerodynamic performance of tandem wings in forward flight in air with different advance ratios ($J = \frac{U_\infty}{2\Theta nL}$) ranging from 0 to 0.75, which corresponded St ranging from 0.67 to 3.3. They found that 60° was the most beneficial in terms of thrust generation at high advance ratios. But the most favourable phase difference for lift generation varied as J was increased. The flow fields through a cycle were presented. Separated and attached flows were observed at low and high advance ratio flights, respectively. At medium advance ratio, LEV was found on the forewing during the downstroke. Similar to the study in hovering flight (Sun & Lan, 2004), the interactions between the forewing and hindwing were found to be detrimental to the lift and resultant forces, and the detrimental effects could be reduced as the advance ratio was increased in the forward flight.

Wang & Russell (2007) computed the aerodynamic force and power by reconstructing a 2D motion from videos captured for a tethered dragonfly at

$Re = 200$. Their results indicated that 180° -phased flight consumed nearly minimal power to meet the force required for balancing the weight, while 0° -phased flight generated maximum lift (see Figure 1.1(i)). The downwash flow induced by one wing on the other wing was analyzed to explain the interaction between forewing and hindwing.

Figure 1.1: (i) The lift and power required at different phase differences (Wang & Russell, 2007); (b) Aerodynamic efficiency of combined forewing and hindwing at different phase differences, with (i) single forewing and (ii) single hindwing as the references (Usherwood & Lehmann, 2008).

Zhang & Lu (2009) systematically studied the aerodynamic performance of gliding dragonfly flight by performing a numerical simulation on 2D flat-plate models in air. Various angles-of-attack (0° - 6° for forewing and 6° - 14° for hindwing), horizontal ($0.05C$ - $0.3C$) and vertical (0 - $0.6C$) wing-wing separations, Reynolds numbers (300, 1,000 and 2,000) were employed to investigate their effects on the lift and drag coefficients, and lift/drag ratio. Both lift and lift/drag ratio of forewing reached peaks when vertical wing-wing separation was $0.16C$, while decreased monotonically with horizontal wing-wing separation. For the hindwing, both lift and lift/drag ratio increased with horizontal and vertical wing-wing separations. The forewing-hindwing interactions were found to enhance the total lift force and reduce the drag force on the tandem wings as

compared to two isolated wings. By analyzing the flow fields, triangular camber effect by which the relative arrangement of the forewing and hindwing was modulated, was found to account for the enhancement aerodynamic performance.

2D numerical study in air was carried out by Hsieh *et al.* (2010) to study the aerodynamics of a dragonfly from the perspective of many-body force decomposition and the associated force elements. The wing models were under combined plunging/pitching motion at $Re = 625$ in hovering flight. By analysing the flow fields at specified time instances, they associated high lift and thrust with three mechanisms: 1) In 0° -phased case, the forewing and hindwing shared lift elements which led to the highest lift of 0° -phased case; 2) The LEV of the hindwing merged with the shed TEV of the forewing, which increased the pressure difference between the ventral and dorsal surfaces of wing model, thus generating the highest thrust on the hindwing in 90° -phased case; 3) During the downstroke motion of the hindwing at 180° phase difference, the hindwing caught the shed LEV of the forewing to make use its positive lift elements. Furthermore, during the upstroke motion of the hindwing, the shed TEV of the forewing and the shed LEV of the hindwing merged, which then attached to the hindwing when it began a downstroke motion. (see Figure 1.2)

Lim & Tay (2010) numerically investigated the effects of phase difference and distance between two s1020 wings on the thrust and lift production at $Re \approx 10^3$ in a forward flight. Phase differences between forewing and hindwing ranging from -180° to 150° and wings separations ranging from 1.25 to 2.5 chord lengths were studied. The wings separated by 1.7 to 2.0 chord lengths showed significant favorable effects on the aerodynamic performance. The average thrust coefficient of the tandem arrangement was found to be more than twice that of the single wing when the hindwing led the forewing by 90° .

(i). $\Psi = 0$ at $t/T = 6.28$

(ii). $\Psi = \pi/2$ at $t/T = 6.67$

(iii). $\Psi = \pi$ at $t/T = 6.0$

(iv). $\Psi = \pi$ at $t/T = 6.5$

Figure 1.2: Vorticity contours and force elements contours at different time for $\Psi = 0$, $\Psi = \pi/2$ and $\Psi = \pi$ from Hsieh *et al.* (2010). (a) vorticity contour; (b) lift force elements contour of the forewing; (c) lift force elements contour of the hindwing.

Broering *et al.* (2012) numerically investigated the aerodynamic performance of 2D tandem wings undergoing plunging and pitching motion at $Re \approx 10^4$ and at a Strouhal number of $St = 0.3$. The 0° phase difference was found to contribute towards high thrust at high propulsive efficiency, but led to low lift efficiency. The 90° and 180° -phased flights obtained less thrust, but consumed less power than the 0° -phased flight since the hindwing extracted energy from the wake of the forewing. Flow fields at specified time instances were analysed for 0° , 90° and 180° -phased cases. Comparing the flow fields, they found that the phase differences had a noticeable effect on the size of the LEV on the hindwings, which showed constructive vortex interactions in 0° -phased case but destructive vortex interactions in 90° and 180° -phased cases.

A large amount of experimental work has also been carried out to investigate the flow fields of tandem wings. Maybury & Lehmann (2004) studied the force generation at various phase lags from -180° to 180° between two flapping robotic insect wings in hovering flight at $Re \approx 100$. The two wings were immersed in a glass tank filled with mineral oil. Air bubbles were used as seeding particles in DPIV measurements. Their results were presented in Figure 1.3. Total lift production was found to be maximized at 0° phase difference for the tandem wings, but at 90° phase difference for the hindwing. The wakes produced by the tandem wings through the flapping cycle for both 90° and -90° -phased cases were highlighted by air bubbles in the mineral oil which were illuminated by conventional fiber optics. Comparing the flow fields of two cases, it was shown that the wake of 90° -phased case was approximately 18% narrower than the 90° -phased case, which could explain the higher lift-to-drag ratio of the 90° -phased case. According to phase-locked PIV measurements at specified time instances, they found that the forewing-hindwing interaction mainly affected the LEV on the hindwing and the strength and orientation of the local flow vector around

the hindwing. When the spacing was larger than 5 times the chord length, the interaction between the wings became very weak (see Figure 1.4(i)). Lehmann (2009) then estimated the instantaneous aerodynamic power and found that the aerodynamic power requirements could be reduced by up to 22% at the phase difference of 90° .

Figure 1.3: Alterations in total lift and lift-to-drag ratio of the model forewing and hindwing in response to changes in kinematic phase shift between both wings. Lift averaged over an entire stroke cycle (closed red circles) and lift-to-drag ratio (closed blue circles) are shown for the forewing flapping on top of the hindwing (B), the hindwing (C) and the combined performance of both forewing and hindwing (D) during various kinematic phase relationships. Performances of single wings flapping without wakewing interaction are shown as solid lines in the respective color. Data are presented for the robotic wings vertically separated by 1.3 (closed circles) and 5.0 (open circles) mean forewing chord lengths. (Maybury & Lehmann, 2004)

Thomas *et al.* (2004) carried out qualitative free- and tethered flight flow visualization on real dragonflies. In 180° -phased case which was used in normal free flight, a LEV on the forewing downstroke, attached flow on the forewing upstroke, and attached flow on the hindwing throughout, were observed. In

Figure 1.4: (i) Modulation of hindwing lift depends on the distance between forewing and hindwing (Maybury & Lehmann, 2004); (ii) Modulation of thrust coefficients generated by tandem wings depends on the distance between forewing and hindwing (Kumar & Hu, 2011).

0° -phased case, a single LEV attached across the forewing and hindwing was found. This study also showed that spanwise flow was not a dominant feature of the flow field.

Yamamoto & Isogai (2005) examined the effects of the flow interaction between two flat-plate wings which were made of 1.2 mm stainless steel sheets in a water tank. The mechanical dragonfly model was studied in hovering flight with phase lags ranging from 0 to 90° in water. The wing models were four times larger than the real dragonfly and flapping at $Re = 5.62 \times 10^3$. Within phase lags of 0 to 90° , the lift force decreased as the phase lags increased. But the differences were found to be quite small within 0 to 90° phase lags.

Lu *et al.* (2007) conducted dye flow visualizations on hovering electromechanical dragonfly-like models in a water tunnel at $Re \approx 2 \times 10^3$. The integral flow structures and their evolutions in 0° , 90° and 180° -phased cases were presented. Except the hindwing in 0° -phased case the forewing in the 90° -phased case, the other two-wing cases all obtained weaker LEVs than that of the single wing. This result showed that the interactions between forewing-hindwing in most cases were detrimental to the LEVs. This effect was attenuated with an

increase in the wing-root spacing.

In the study of 3D mechanical dragonfly wings like models, Usherwood & Lehmann (2008) investigated the instantaneous aerodynamic power and aerodynamic efficiency in a tank with mineral oil. They estimated the aerodynamic efficiency by Figure of Merit, a special case of propeller efficiency used for hovering helicopters, which was different from the other studies. They found that the aerodynamic power requirements could be reduced by up to 22% at phase lag of 90° compared with a single pair of wings at the appropriate forewing-hindwing phasing (Fig 1.1(ii)). By analysing the wake patterns, the improvement was found to be achieved by recovering energy from the wake wasted as swirl in a manner analogous to coaxial contra-rotating helicopter rotors.

Rival *et al.* (2010, 2011*a,b*) made several efforts to study the force evolution, power efficiency and associated vortex dynamics of two tandem wings. In hovering flight at $Re = 3 \times 10^3$ (Rival *et al.*, 2011*b*), tandem wings with forewing and hindwing both undergoing pitching and plunging motion were investigated in a plexiglass chamber. They performed phase-locked PIV measurements in 90° -phased case, which was the only case that was capable of generating similar levels of thrust as compared to the single-wing case. By analyzing the flow fields through the whole cycle, they found that the forewing's TEV encouraged an earlier formation of the hindwing's LEV, which further changed the interaction between the LEV and TEV of hindwing. These interactions contributed to a more constant production of thrust over the cycle as compared to the single-wing case.

They also studied the forward flights at $Re = 3 \times 10^4$ and $St = 0.125$ (Rival *et al.*, 2010, 2011*a*) in wind tunnel. Rival *et al.* (2010) investigated the vortex interaction of two tandem wings with the forewing oscillating in pure-plunging motion based on a simple harmonic motion at an angle-of-attack of 8° , while the

hindwing was fixed at three positions which were 0, -0.25 and -0.5 chord length from the center position of the forewings stroke at angles-of-attack of 0° and 8° . The main parameter influencing the vortical interaction was identified as the angle-of-attack rather than the vertical spacing between wings. They found that the combined mean lift was not increased in tandem configuration, but the combined drag was reduced for certain configurations due to TEV-induced leading-edge suction on the hindwing. 90° phase difference was found to lead to the largest thrust. The results of phase-locked PIV measurements showed that tandem arrangements produced stronger vortices. In certain cases, the vortices were found to dissipate quicker in the wake.

Figure 1.5: (i) Development of leading-edge suction on forewing for $\Psi = 90^\circ$ at $t/T = 0.417$; (ii) Interaction of TEV on hindwing for $\Psi = 60^\circ$ at $t/T = 0.500$. (Rival *et al.*, 2011a)

Rival *et al.* (2011a) further investigated the recovery of energy from leading and trailing edge vortices in forward flight both experimentally and numerically. The forewing was undergoing plunging motion with an angle-of-attack of 8° , while the hindwing was undergoing combined plunging and pitching motion. According to the flow fields at specified time instances, they identified two types of vortex interactions as shown in Figure 1.5: 1) The LEV of forewing induced a separation on the lower surface of the hindwing at 60° , 90° and 120° phase differences, which generated a strong suction region that contributed to the thrust generation; 2) The TEV of forewing induced a separation on the upper surface of the hindwing at 0° , 30° and 60° , which induced a relatively strong

suction normal to the wing to benefit the lift generation.

Lee (2011) investigated the interactions of the wakes from the upstream wing and the downstream wing in forward flight at $Re=8.5 \times 10^4$ with phased-locked PIV and surface pressure measurements in a wind tunnel. The results showed that the wings at a phase difference of 180° performed better than the wings at a phase difference of 0° with a larger lift force coefficient, especially at wings separation of 1.3 chord lengths. The results of PIV measurements showed that the downwash induced by the upstream wing disrupted the LEV formation at both phase differences of 0° and 180° , which explained the lower lift coefficients of tandem wings compared with the single wing.

Kumar & Hu (2011) investigated the effects of wing spacing between tandem piezoelectric wings on wake vortex structures and thrust by PIV and forces measurements in a wind tunnel. The measurements were performed at wing spacing values of 0.15C, 0.5C, 1C, 1.5C and 2C, where C was the chord length. The results indicated that the wake structures generated was severely influenced by the spacing. When the spacing was too small (0.15C) or too large (2C), the wings began to act as either a single entity or two separate wings operating independently. The effect on the thrust is shown in Fig 1.4(ii).

1.2.2 Aerodynamic performance of flexible wings

The wing models used in the majority of past studies on tandem wings were rigid ones. However, the real dragonfly wings showed significant wing deformations in both chordwise and spanwise directions (Koehler *et al.*, 2012). A lot of numerical and experimental research studies have identified the wing flexibility of insects as one of key factors accounting for their superior aerodynamic performance.

In Miao & Ho (2006), they numerically investigated the effects of chordwise

flexure amplitude on the aerodynamic performance of a plunging wing in forward flight at various combinations of Reynolds number and reduced frequency. An enhancement in the propulsive efficiency was observed on the wing models with intermediate chordwise flexibility. The highest propulsive efficiency corresponded to $St = 0.255$. At $Re = 10^4$, thrust-indicative wake structures were found in the unsteady flow fields through a cycle when the flexure amplitude of the wing, i.e. the amplitude of deformation at trailing edge, was less than 0.5 of the chord length. This wake evolved into a drag-indicative form as the flexure amplitude increased to 0.6 and 0.7 of the chord length.

In the study of Zhu (2007) at $Re = 2 \times 10^4$ and $St = 0.2$, they investigated the effects of chordwise and spanwise flexibilities on the thrust and propulsive efficiency in both air and water. In air, the deformation was mainly caused by inertia of the wing. The chordwise flexibility was found to reduce both the thrust and the propulsive efficiency, while the spanwise flexibility increased the thrust without efficiency reduction within a small range of structural parameters. In water, the fluid loading showed significant impact. The chordwise flexibility increased the efficiency while the spanwise flexibility reduced both the thrust and efficiency.

Vanella *et al.* (2009) conducted numerical investigations on a two-dimensional two-link model in hovering flight within a viscous fluid. Three Reynolds numbers were considered ($Re = 75, 250$ and $1,000$) to investigate the effect of the reduction in viscous dissipation on the system dynamics. The best performance in terms of lift generation was obtained when the wing was excited at $1/3$ of its natural frequency. This enhancement was found at all Reynolds numbers studied. The flow fields at specified time instance, as well as the flow fields through a cycle, were compared between the rigid and flexible wings. Enhancement of wake capture mechanism on flexible wing was observed. It was caused by a

stronger flow around the wing at stroke reversal, resulting from a stronger end of stroke vortex at the trailing edge.

In Michelin & Smith (2009), they numerically investigated the effect of chordwise flexibility on the propulsive performance of a heaving wing in forward flight. The results showed that while the mean thrust could increase with an increase in flexibility, the wing was too flexible to transfer momentum to the flow below a certain threshold. Too much flexibility, however, create a net drag. The flexible wing with an appropriate flexibility was found to generate stronger wakes which accounted for the increased mean thrust. The energy consumption was also increased for the flexible wing, but more slowly than the mean thrust, thus leading to a net increase in the flapping efficiency.

Young *et al.* (2009) analysed the aerodynamic consequences of wing deformation of locusts using a 3D computational fluid dynamics simulation based on detailed wing kinematics in forward flight. The simulation is performed in air. To investigate the effects of wing topography and deformation, they first removed the camber while keeping the same time-varying twist distribution, and then removed both camber and spanwise twist. Comparing the flow fields with and without camber and twist deformation, where the reversed flow appeared on the top surface of wing models, the model with both camber and twist deformations was found to be free from flow separations due to the curvature of the wing section and the reduced local angle-of-attack at the leading edge. For both the efficiencies of lift and resultant force, the full-fidelity model obtained higher values than the other two models.

Kang *et al.* (2011) computationally studied plunging wings which were flexible in both chordwise and spanwise directions in forward flight in water, as well as hovering isotropic flapping Zimmerman wings in air. They found that the maximum propulsive efficiency was obtained when the motion was near the

natural frequency, whereas the optimal propulsive efficiency was reached when the wing was moving at about half of the natural frequency. They established scaling relationships to guide the design and performance analysis of micro air vehicles.

Nakata & Liu (2012*b*) developed a fluid-structure interaction model by loosely coupling a finite element method based computational structural dynamic model and a computational fluid dynamic based insect dynamic flight simulator. They (Nakata & Liu, 2012*a*) then used it to numerically study the aerodynamic performance of flexible hawkmoth wing in hovering flight at $Re = 6,3 \times 10^3$ in air. A rigid wing and three rigid wings with prescribed spanwise bending, twist and camber were also investigated. With same kinematics as inputs at the wing bases, the flexible wing could obtain 19.4% higher average vertical force and 8.5% higher efficiency than the rigid wing. The spanwise bending and twist deformations were found to be the main reasons account for the vertical force and efficiency enhancements, respectively. With the spanwise bending deformation, the flexible wing delayed the breakdown of LEV near the wing tip, which benefited the aerodynamic force production. Besides, the bending and twist deformation modified the kinematics in the distal area, thus resulting the aerodynamic force enhancement. The twist deformation resulted in a modification in direction of spanwise wing cross section, thus the direction of force vectors. Last, a stronger downwash flow was created by the flexible wing during a rapid stroke reversal, which also contributed to the enhanced aerodynamic performance.

In addition to the above numerical simulations, a large number of experimental studies on single wings also found that appropriate flexibility would help improve the aerodynamic performance. In the study by Prempraneerach *et al.* (2003), they experimentally studied the effect of chordwise flexibil-

ity on the propulsive efficiency and thrust during plunging/pitching motion at $Re = 4 \times 10^4$ and $St = 0.1 \sim 0.45$ in a water tank. With proper flexibility, the flexible wing was able to improve efficiency with only a small decrease in thrust generation. In both the kinematic modes studied, the efficiency was increased when Strouhal number was below 0.45 with properly selected flexibility, even up to 36% relative to the rigid wing.

Heathcote *et al.* (2004) investigated the thrust generation of plunging tear-drop flexible wings in hovering flight with Reynolds numbers ranging from 8×10^3 to 2.1×10^4 in a water tank. Both PIV and direct force measurements were carried out. The results showed that the thrust coefficient of the wing with intermediate stiffness was the highest at high plunging frequencies, while the wing with minimum stiffness could generate larger thrust at low frequencies. The results suggested that there was an optimum flexibility to produce larger thrust and thrust/input-power ratio for a given plunging frequency and amplitude. Following their study, Yang (2011) used the tear-drop wing in CFD simulation to study the effect of flexibility on the thrust and obtained similar conclusions.

Figure 1.6: (i) Thrust coefficient as a function of Strouhal number; (ii) Propulsive efficiency as a function of Strouhal number .(Heathcote *et al.*, 2008)

In Heathcote & Gursul (2007), they experimentally investigated the thrust generation of tear-drop flexible wings in forward flight with Reynolds numbers ranging from 9×10^3 to 2.7×10^4 in a water tunnel. An intermediate flexibility was found to increase both thrust coefficient and propulsive efficiency. The flow fields obtained by PIV measurements showed stronger TEVs corresponding to higher thrust coefficients, and weaker LEVs corresponding to higher efficiencies.

Heathcote *et al.* (2008) also studied the effect of spanwise flexibility on the thrust generation of rectangular wings oscillating in pure heave during forward flight in a water tunnel. The thrust benefit was as high as 50% for a wing of appropriate flexibility. The effects of Strouhal number on the thrust and propulsive efficiency were presented in Figure 1.6. The range of Strouhal number within which the spanwise flexibility offered benefits overlapped the range found in nature, i.e. $0.2 \sim 0.4$. With PIV measurements, a moderately stronger TEV system was observed in the case with appropriate flexibility. In the case with excessive spanwise flexibility, vortices at the wing root and tip were found to shed with opposite signs, which resulted in a weak and fragmented vorticity pattern. Following their study, Gordnier *et al.* (2013) performed simulation work to investigate the effect of spanwise flexibility. Good agreement with the work of Heathcote *et al.* (2008) was obtained.

Hu *et al.* (2008) conducted PIV measurements to quantify the transient behavior of vortex and turbulent flow structures around flexible-membrane wings in steady flight at different AOAs in a wind tunnel. The results of aerodynamic force measurements elucidated clearly that the flexible-membrane wings with appropriate flexibility could provide higher lift, lower drag and thus higher lift to drag ratio than the rigid wing. The difference increased especially at angle of attack ranging from 0° to 12° . PIV results showed clearly that the flexible-membrane wings varied their camber which helped to balance the pres-

Figure 1.7: (i) Vector field of the rigid thin wing at AOA = 10 deg; (ii) Vector field of the flexible thin wing at AOA = 10 deg. (Hu *et al.*, 2008)

sure differences on the upper and lower surfaces of the wings, thus suppressing large-scale flow separation (see Figure 1.7). Meanwhile, significant deflections at the trailing-edge were found to help reduce the effective angles of attack, thereby delaying wings stall at high angles of attack.

Kim *et al.* (2009) investigated the effects of camber and chordwise flexibilities on a flexible adaptive flapping wing in a wind tunnel. To evaluate the effects of chordwise flexibility on the aerodynamic performance, they carried out low-speed wind tunnel tests under both static and dynamic test conditions. PIV measurements were performed to investigate the flow fields. In static flight, stall delay and drag reduction were observed since the effective angle of attack was reduced due to the chordwise flexibility. In flapping flight, the flexibility could help the wing stabilize the LEV to offer an increase in lift generation.

Mountcastle & Daniel (2009) investigated how wing flexibility affected the overall induced flow of real hawkmoth using PIV measurements. They found that the flexible wings yielded mean advective flows with substantially greater magnitudes and orientations more beneficial to lift generation than those of rigid wings. In their study, spanwise bending was observed in both robotically actuated and natural flight. However, how the transverse bending might

contribute to the induced flow field was not investigated.

Zhao *et al.* (2010) studied the effect of veins on the aerodynamic performance in a tank with oil. Three models, each with a single vein in addition to the leading edge, were investigated. The veins were glued to a wing based on Polyes0.002 which was the most flexible material in their study. The angles between the vein and leading edge were 20° , 40° and 60° . The results of Polyes0.002 wings with and without veins were compared with that of PET-G0.006 wing which was the most rigid wing. The veins were found to improve the aerodynamic performance of flexible wings. The lift-to-drag ratios of models with angle of 40° and 60° were both increased comparing with the Polyes0.002 wings without veins and PET-G0.006 wing.

Lua *et al.* (2010) investigated the effects of wing flexibility on the aerodynamic forces generations of a hawkmoth wing model executing hawkmoth flapping motion and a simple harmonic motion in hovering flight. The experiments were conducted in a water tank. The hawkmoth motion was conducted at $Re = 7.254 \times 10^3$, while the simple harmonic flapping motion at $Re = 7.8 \times 10^3$ and 1.17×10^4 . Eight wing models, i.e. one rigid and seven flexible wings, were investigated in the experiments. Their results showed that wings with stiffness above the critical value could deliver mean lift coefficient close to that of a rigid wing when executing hawkmoth motion, but lower than the rigid wing when undergoing a simple harmonic motion. Flexible wings with and without veins were both investigated. The non-homogenous wings (with veins) were found to have better characteristics. Flow visualization was also carried out for the rigid wing executing both the hawkmoth flapping motion and the simple harmonic motion, but not for the flexible wings.

In Wissa *et al.* (2012), they presented an optimal compliant spine concept for ornithopter applications. Membrane wings were investigated in air. The

compliant spine resulted in a spanwise bending deformation of the wing models. The effect of inserting the compliant spine into the wings on the electric power required and the aerodynamic loads was studied. With the compliant spines, the ornithopter consumed 45% less power and produced an additional 16% of its weight in mean lift compared to the same ornithopter without the compliant spine.

Besides the numerical and experimental studies, Kang & Shyy (2014) developed an analytical model for fluid-structure interactions of a flexible flat-plate wing in mineral oil during hovering flight. The ratio between the plunging motion frequency and the first natural frequency of the wing varied from 0 to 0.4. Their results on lift and wing deformation agreed well with those of high-fidelity model.

1.3 Motivation and scope of the present research

The earlier studies have offered a lot of information on how the tandem configuration and flexibility affect the aerodynamic performance. However, almost all of them concerned with the effects of the tandem arrangement and the wing flexibility separately. To authors' knowledge, only Warkentin & DeLaurier (2007) studied both effects with tandem membrane wings undergoing flapping motions at $Re = 3 \times 10^4$ and $St = 0.32 \sim 0.8$ in a wind tunnel. Their results showed that wings' spacing on the order of one chord length was generally best, and phase differences of approximately $0 \pm 50^\circ$ gave the highest propulsive efficiencies. The optimum tandem-wing arrangement could even obtained efficiencies nearly twice as large as that of the single wing. However, their study provided little information on how the flexibilities would affect the aerodynamic perfor-

mance of flexible tandem wings, since only one set of membrane wings was used without varying the flexibility of wings. The information on the flow fields was not provided either.

In nature, the real dragonflies have the features of both tandem configuration and flexible wings which together lead to their great aerodynamic performance. Inspired by the real dragonflies, it will be meaningful to investigate how wing flexibility will affect the interaction of tandem wings, as well as how the interaction will change the performance of flexible wings. Therefore, the combined effect of the flexibility and tandem configuration of the dragonflies requires further study. The present effort is meant to contribute in this regard. By studying the aerodynamic performance of flexible tandem wings, a better understanding of the dragonfly flight will be offered to contribute to the development of MAVs.

The scope of this study consists of three parts. In the first part, the mechanisms of forewing-hindwing interactions for rigid tandem wings were investigated through the force and phase-locked PIV measurements. The tandem wings were investigated in both hovering and forward flights to provide more comprehensive information on the aerodynamic performance of the tandem wings. Moreover, by comparing the the hovering and forward flights, the effects of incoming flow on the interaction was also investigated.

In the second part, force measurements were carried out in both hovering and forward flights for the flexible tandem wings, with the rigid tandem wings as the reference. 2D deformation and phase-locked PIV measurements at time instances of interest were also carried out to explain the differences between the aerodynamic performance of flexible and rigid tandem wings.

As an important part of the aerodynamic performance, force dynamics were found to be affected significantly by both the phase difference and flexibility from the results of second part. Therefore, in the third part, 3D deformation and

time-resolved PIV measurements were performed to investigate the evolution of the flow fields in different tandem cases. By comparing the dynamics of flow fields, the mechanisms for the differences in the force dynamics will be explained.

Chapter 2

Experimental setups and procedures

This chapter summarizes all experimental setups and procedures employed in this study. First, the preparations of the experimental work which include the flow facilities, the realization of wings' motion and the fabrication of wing models will be introduced. Then, all the experimental measurements on the aerodynamic performance, i.e. the force, phase-locked PIV, time-resolved PIV and deformation measurements, will be described in details.

2.1 Flow facility

In this study, both hovering and forward flights were investigated. For hovering flight, all the measurements were carried out in a 500 mm(W) $\times$ 600 mm(H) $\times$ 1200 mm(L) plexiglass water tank. For forward flight measurements, a free-surface closed-loop low-speed water tunnel located at Water Tunnel Laboratory in NTU was employed. As shown in Figure 2.1, the water is pumped into the water tunnel via the inlet by a axial pump, then is conditioned by a honey comb and an array of fine mesh screens to maximize uniformity and minimize turbulence intensity. Before entering the test section, the flow passes through a contraction section with a 4-to-1 contraction ratio. The test section which is made of tempered glass has dimensions of 450 mm(W) $\times$ 600 mm(H) $\times$ 1100 mm(L). After the test section, the flow is discharged at outlet and delivered back to the inlet.

Figure 2.1: Schematic of the the water tunnel (*This figure was used with permission of Bin Zang who produced it*).

At a water level depth of 450 mm, the water tunnel can reach a maximum flow speed at approximately 0.2 m/s. The flow speed U_∞ is linearly proportional to the frequency of the pump n , which is shown as following equation,

$$U_\infty = 0.0034n + 0.0008. \quad (2.1)$$

Therefore the flow speed can be set easily by adjusting the frequency of the pump. In present study, the flow speed required is 0.15 m/s which corresponds to a pump frequency at 43.9 Hz. Before carry out the experiment, the flow velocity was validated by PIV measurement. Based on the mean chord length of forewing and the incoming flow speed, the Reynolds number is $Re_{U_\infty} = \frac{U_\infty \bar{C}_{fore}}{\nu} = 3,873$.

2.2 Wings' kinematics

In the current study, the wing models are undergoing a combined pitching (α) and plunging (h) motion. The pitching and plunging motion of the forewing (*fore*) and hindwing (*hind*) are described by the following equations (1) to (4)

$$h_{fore} = h_0 \cos(2\pi ft) \quad (2.2)$$

$$\alpha_{fore} = \alpha_0 \cos(2\pi ft + \Phi) \quad (2.3)$$

$$h_{hind} = h_0 \cos(2\pi ft + \Psi) \quad (2.4)$$

$$\alpha_{hind} = \alpha_0 \cos(2\pi ft + \Phi + \Psi), \quad (2.5)$$

where Ψ is the phase difference that the hindwing leads the forewing, f is the oscillating frequency, and Φ is the phase angle that the pitching motion leads the plunging motion. Φ was set at 90° herein since pitching leading plunging motion by 90° has been shown to be most efficient from a number of sources (Jones *et al.*, 2001; Ramamurti & Sandberg, 2001). So far previous studies have found three phase differences at which the dragonflies usually fly: i) 0° -phased flight is usually used upon take-off, accelerating and hovering (Alexander, 1984, 1986; Ruppell, 1989); ii) 90° -phased flight is often used during straightforward escape and maneuvering flight (Azuma & Watanabe, 1988; Wakeling & Ellington, 1997*b*); iii) 180° -phase difference is applied in cruising flight generally and hovering as well (Alexander, 1986; Wakeling & Ellington, 1997*b*; Norberg, 1975; Thomas *et al.*, 2004). Therefore three phase differences between the forewing and hindwing at $\Psi=0^\circ$, 90° and 180° were considered in the current study. The forewing and hindwing were separated by 1.5 chord length of forewing at the quarter-chord position, which has been proven to be appropriate separation for the forewing-hindwing interaction (Maybury & Lehmann, 2004; Kumar & Hu, 2011). Wakeling & Ellington (1997*b*) filmed the drag-

onflies (*Sympetrum sanguineum*) to investigate their kinematics. They found that the average stroke of wing beat is about 90 degrees. So the amplitude of stroke at mid-span position can be evaluated approximately as $\frac{L}{2} \sin 45^\circ$ in flapping flight, where L is the wing length. In the present study, we chose the amplitude of stroke at mid-span position in flapping flight as our plunging amplitude. Therefore, $h_0 = \frac{L_{fore}}{2} \sin 45^\circ = 44mm$ was set based on the length of forewing L_{fore} . The pitching amplitude was set at $\alpha_0 = 30^\circ$ as in previous studies such as Rival *et al.* (2011b). In hovering flight, the oscillating frequency was $f = 1Hz$, corresponding to a Reynolds number, based on the mean chord length of forewing and mean plunging velocity, $\bar{U}_P$, of $Re_{\bar{U}_P} = \frac{\bar{U}_P \bar{C}_{fore}}{\nu} = 4,544$. In forward flight, two oscillation frequencies of $1Hz$ and $0.5Hz$ were studied, corresponding to Strouhal numbers $St = \frac{2fh_0}{U_\infty} = 0.6$ and 0.3 , and Reynolds numbers $Re_{\bar{U}_P} = \frac{\bar{U}_P \bar{C}_{fore}}{\nu} = 4,544$ and $2,272$, respectively. The Reynolds and Strouhal numbers studied herein are summarized in table 2.1 and the time histories of the positions and angles of attack of both forewing and hindwing at three phase differences studied, without demonstration of wing's deformation during the motions, are schematically illustrated in Figure 2.2.

Figure 2.3 illustrates the system to realize the motions of the forewing and hindwing. It consists of four components, i.e. motors, controllers, power supply and computer. Two linear servo motors and two rotary servo motors were employed. The linear servo motors of type LinMot PS01-37 $\times$ 120F-HP-C (maximum force: 255 N, repeatability: $\pm 0.05mm$, resolution: 0.05mm) were used to drive the plunging motion while the rotary servo motors of type Maxon Ec-max 30 BL (maximum torque: 33.4 mN $\cdot$ m, resolution: 0.01 $^\circ$) were used to drive the pitching motion. The rotary motor had a gearhead with reduction 14:1 assembled to amplify the maximum torque. The rotary motors were mounted on the top of linear sliders so that the wing models could be driven to plunge and

Table 2.1: Non-dimensional parameters in hovering and forward flights

	$Re_{\overline{U}_P}$	Re_{U_∞}	St
Hovering Flight	4544	-	-
Forward Flight at $f = 1Hz$	4544	3873	0.6
Forward Flight at $f = 0.5Hz$	2272	3873	0.3

$Re_{\overline{U}_P} = \frac{\overline{U}_P \overline{C}_{fore}}{\nu}$, where $\overline{U}_P$ is the mean plunging velocity, $\overline{C}_{fore}$ is the mean chord length of the fore wing. $Re_{U_\infty} = \frac{U_\infty \overline{C}_{fore}}{\nu}$, where U_∞ is the incoming flow.

pitch simultaneously. Because of the imbalance of load on the linear motor, the shaft of linear motor kept rotating on its axis. To solve this problem, a linear bearing and shaft were added. The shaft of linear bearing and linear slider were connected so that the rotation of the slider was restrained (see Figure 2.3).

All the motors were controlled by LinMot E1100-GP-HC controllers. As shown in Figure 2.4, R1, L1, R2 and L2 are the controllers which served the rotary and linear motors for the forewing, and the rotary and linear motors for the hindwing, respectively. A power supply (LinMot T01-72-420) with input of 240V AC single-phase power at port X9 and output of 72V DC power at port X10 was used to power up the four motors simultaneously via the controllers at ports X7. Four controllers shared the earth wire by connecting their Bus Termination Ports (X7), which was also connected to the power supply. 24V DC power was supplied to serve the controllers at ports X5. For the rotary motors, the controllers communicated with the motors via the Motor Signal (X3) and External Encoder (X8) Ports. As for the linear motors, the motors were controlled via Motor Signal (X3) and Motor Phases (X2) Ports. To realize the 90° phase lag between pitching and plunging motion, as well as the phase differences between the forewing and hindwing, the triggering signals were transferred between the controllers at Triggering Signal Ports (X4). As shown in Figure 2.4, the controller R1 was set as master with the controllers

Figure 2.2: (a)-(c) Time histories of position and angles of attack of both forewing and hindwing at phase differences of (a) $\Psi=0^\circ$, (b) $\Psi=90^\circ$ and (c) $\Psi=180^\circ$, respectively, without demonstration of the flexible wings' deformation during the motion. The solid lines and open circles indicate the upstroke, while the dashed lines and filled circles indicate the downstroke. The wing models are in acceleration in the plunging direction during the first half of both upstroke and downstroke, while in deceleration during the last half of both stroke motions. The numbers in the circles indicate the selected sequences, starting from number 1, of the motion in a cycle. Note that at different phases of Ψ , the starting sequences of number 1 for forewing and hindwing are at different locations within a cycle. (d) Definition of force vectors on the wing. F_C and F_N are forces parallel and normal to the wing which are measured by the force sensor directly. F_H and F_V are horizontal and vertical forces which are normal and parallel to the plunging direction, respectively. "L.E." represents the leading edge of the wing, which is marked by a relatively large black dot at one end of the wing.

Figure 2.3: System for the realization of motions

L1 and R2 as its slaves. Signals were sent from R1 via Triggering Signal Ports (X4) to trigger L1 and R2. Similarly, the R2 acted as the master of L2. By setting the timing of triggering, the phase lags were achieved. The RS232 Ports (X8) allowed the communication between the controllers and the computer via RS232 cables. Motions of motors and the timing for triggers were programmed in software *LinMot-Talk 5.0* on the computer. Figure 2.5 showed a snapshot of the software with the programming for the R1 presented. In the 'Project' tree window, each controller corresponded to a sub-project. Simple harmonic motions can be created and joined in the 'Curve' tool to achieved desired motor motion profiles. The plunging and pitching motions of both forewing and hindwing were therefore pre-defined and uploaded to each controller. In 'Command Table' tool, the time lag between the plunging and pitching motions, as well as the time lags between forewing and hindwing were achieved. As shown in Figure 2.5, the programming was used to realize the 90° phase lag between the

pitching and plunging motion and 180° phase difference between the forewing and hindwing at $f = 1Hz$. The pitching motion of R1 was started at first. After waiting for $T/4 = 250ms$, the plunging motion of L1 was triggered by switching on the I/O port X4.4. To realize the phase difference of 180° between forewing and hindwing, the I/O port X4.6 was switched on after another $T/4 = 250ms$ to trigger the pitching motion of R2. The plunging motion of L2 was then triggered in the 'Command Table' of R2. The phase differences of 0° and 90° were also achieved by adjusting the time delay to switch on the I/O port X4.6. The triggering was physically realized on the controllers at X4 ports indicated in Figure 2.4.

With the motions realized, the wing models were mounted on the rotary motor as shown in Figure 2.8. The rotational axis was a quarter chord-length away from the leading edge of the wing models. To immerse the wing models in the vertical center of the water tank and water tunnel, carbon fiber tubes were used to extend the length of wing models. The long tubes were then mounted on the rotational axis of rotary motor. Both the carbon fiber tubes and the adapters connecting the rotary motors and the carbon fiber tubes were rigid enough that the wing models were driven to plunge and rotate precisely as programmed.

2.3 Wing models

Wing models used in this study are shown in Figure 2.6. The planforms of wing models were adopted from the real dragonfly (*sympetrum-fonscolombei*). The span lengths of the forewing and hindwing are 125 mm and 120 mm, respectively, and the mean chord lengths are 26 mm and 35 mm, respectively. Three sets of flexible wing models with different levels of flexibilities were fabricated

Figure 2.4: Wire connections in the motor system

Figure 2.5: Snapshot of the software *LinMot-Talk 5.0*

using a rapid prototyping machine (Objet Eden 260) with Fullcure 720 translucent acrylic-based photopolymer (Young’s modulus: 2870 MPa, Poisson’s ratio: 0.3). Different flexibilities of wing models were achieved by varying the thickness of the wings. Three sets of flexible wing models with thicknesses of 0.5 mm, 0.75 mm and 1 mm were named Wing I, Wing II and Wing III, respectively. Moreover, rigid wing models with the same planforms of the flexible forewing and hindwing were fabricated from an Aluminum (Young’s modulus: 69 GPa, Poisson’s ratio: 0.32) sheet of 1.5 mm thick as the reference for the comparison with flexible wings. The density ratios for the flexible and rigid wings, $\bar{\rho} = \frac{\rho_s}{\rho_f}$, are 1.3 and 2.7, respectively, where ρ_s and ρ_f are the densities of the wing model and water, respectively.

An apparatus was made to measure the flexibilities of wing models quantitatively. The method is similar to that described in Combes & Daniel (2003). Figure 2.7(a) shows a schematic diagram of the flexibility measurement apparatus, which can capture force and displacement simultaneously. A point force

Figure 2.6: Dragonfly-like wing models used in the present study. (a) forewing model, (b) hindwing model.

was applied at 70% of the wing span length on the rotational axis for spanwise stiffness measurements, and at 70% of the chord width at the middle of the wing span for the chordwise stiffness measurements (see Figure 2.7(b)). As shown in Figure 2.7(a), a pin was attached on a force/torque sensor (NANO 17, ATI Industrial Automation, Inc.) and contacted the wing models at the loading point. The sensor was then fixed on a translation stage. When the wing models had no bending deformation, the reading of the force/torque sensor was set to be zero. By moving the translation stage manually, a displacement was applied slowly at the loading point at a rate of about 0.2 mm/s. At the same time, the load at the loading point was recorded by the force/torque sensor on its z axis. The force range and accuracy on z axis are 0-17 N and 3 mN, respectively. The displacement was limited to 5% of the span length and 5% of the chord length in the spanwise and chordwise stiffness measurements, respectively, to ensure that the wing deflections were within the linear elastic range. The wing models were clamped at wing root when measuring the spanwise flexibility, and were clamped along the leading edge when measuring the chordwise flexibility. The reduced flexural stiffness, EI , is modulated by Young's modulus and thickness based on an assumption that the stiffness of a thin wing structure is proportional to Young's modulus and the thickness cubic (Timoshenko & Woinowsky-Krieger, 1959; Combes & Daniel, 2003). Based on simple beam theory, the spanwise and chordwise flexural stiffness can be cal-

Table 2.2: Stiffness of wing models

Wing models	Spanwise stiffness EI_{span} (N m^2)		Chordwise stiffness EI_{chord} (N m^2)	
	forewing	hindwing	forewing	hindwing
I	2.90E-04	7.11E-04	1.46E-03	1.49E-03
II	1.36E-03	1.88E-03	3.59E-03	3.81E-03
III	3.15E-03	8.36E-03	5.08E-03	9.21E-03

culated as $EI_{span} = \frac{FL_{span}^3}{3\omega}$ and $EI_{chord} = \frac{FL_{chord}^3}{3\delta}$, respectively, where L_{span} and L_{chord} are 70% of wing span length and chord width, respectively, E is the Young's modulus of the wing models, I is the second moment of the cross section, ω and δ are displacements caused by the point loads in the spanwise and chordwise stiffness measurements, respectively. The spanwise and chordwise stiffness of the flexible wing models studied herein are listed in table 2.2. Effective stiffness (Π_1) of the flexible wing models are also provided in table 2.3, which give the ratio between the elastic bending forces and the fluid-dynamic forces. It is defined as $\Pi_1 = \frac{Eh_s^3}{12(1-v^2)\rho_f\bar{U}_P^2L_{ref}^3}$, where h_s is the thickness of wing model, L_{ref} is mean chord length for chordwise measurements while wing span length for spanwise measurements, v is Poisson's ratio and $\bar{U}_P$ is mean plunging velocity.

In Lua *et al.* (2010), a rigid hawkmoth-like wing model was also fabricated using 1.5 mm thick Aluminium plate. The span length and mean chord length of the hawkmoth-like wing model were 250 mm and 76 mm, respectively, which are about twice those of the wing model in the present study. EI_{span} of their rigid model is $3.027N \cdot m^2$. Therefore, EI_{span} of the Aluminum wing model in current study can be estimated on the order of 10^0 . Compared with the EI_{span} of the flexible wing models (see Table 2.2), the Aluminum wing model is far more rigid and thereby can be regarded as rigid wing model.

Figure 2.7: Quantitative measurements of the flexibility of flexible wing models. (a) A schematic diagram of the flexibility measurement apparatus. (b) Load points on the forewing and hindwing. L_{fore} and L_{hind} are the span lengths of forewing and hindwing, respectively, while C_{fore_m} and C_{hind_m} are the chord widths at the middle of the wing span of forewing and hindwing, respectively.

Table 2.3: Effective stiffness of wing models

Wing models	Motion frequency $f = 1Hz$				Motion frequency $f = 0.5Hz$			
	Chordwise		Spanwise		Chordwise		Spanwise	
	fore	hind	fore	hind	fore	hind	fore	hind
I	60	25	0.54	0.61	241	99	2.17	2.46
II	204	83	1.83	2.07	815	334	7.33	8.29
III	483	198	4.34	4.91	1931	792	18.24	19.64

2.4 Force measurement

As shown in Figure 2.8, a six-axis force/torque sensor (NANO 17, ATI Industrial Automation, Inc.) was alternately attached to the base of carbon fiber tubes extended from the wing models, and the experiments were repeated to measure the forces and moments on the forewing and hindwing. A unique 6x6 calibration matrix was generated for this sensor by factory to decouple the forces and torques. Before carrying out the measurements, the calibration file was loaded to *ATI DAQ F/T.NET Demo*, a software installed on the computer. During the measurements, this software was used for recording data and performing the matrix calculation for conversion from gauge voltages to exact force and torque values on x, y and z axes. The force ranges for x, y, and z axes are 0-12 N, 0-12 N and 0-17 N, respectively, where z axis is central axis of the force sensor. The moment ranges for all three axes are 0-120 mN·m. The force and moment resolutions are 3 mN and 0.016 mN·m, respectively. The aerodynamic force produced by the wing generally ranged within 0-0.6 N, while the moment ranged within 0-5 mN·m. Data were acquired by a data acquisition card (NI PCI-6221: 16-bit, 250 kS/s) installed on the computer. The sample rate and average level were set to be 16,000 Hz and 80 in software *ATI DAQ F/T.NET Demo*, respectively, which led to an effective sample rate of 200 Hz. The raw data were then passed through a FFT low-pass filter with a cutoff frequency of 10 Hz for the oscillating frequency of $f = 1\text{Hz}$, while the cutoff frequency was 5 Hz when the oscillating frequency was 0.5 Hz. The measured mean force values were observed unchanged when more than two hundred stroke cycles were used for averaging. To avoid transient effects, the first few cycles after the wing motion was started and the last few cycles before the wing motion was stopped were discarded, and only the middle two hundreds stroke cycles were used for data analysis to obtain the following average aerodynamic force

Figure 2.8: Experiment setup for force and PIV measurements. Measurements of the hovering flight were carried out in the water tank while those of forward flight were done in the water tunnel. Camera I was used to capture the seeding particles from the bottom without the mirror installed in the PIV measurements of rigid wings. In the measurements of flexible wings, the camera I was replaced by camera II viewing from the front with the mirror installed.

coefficients, power coefficients, and efficiencies.

The force/torque sensor recorded forces normal (F_N) and parallel (F_C) to the wing surface at any instant of motion. These two forces were then converted to forces in vertical (F_V) and horizontal (F_H) directions using the following equations (see Figure 2.2(d)):

$$F_V = F_N \cos \alpha - F_C \sin \alpha \quad (2.6)$$

$$F_H = -F_N \sin \alpha - F_C \cos \alpha. \quad (2.7)$$

Vertical and horizontal force coefficients were thereafter computed by

$$C_V = \frac{2F_V}{\rho \bar{U}_P^2 S} \quad (2.8)$$

$$C_H = \frac{2F_H}{\rho \bar{U}_P^2 S}, \quad (2.9)$$

where $\overline{U}_P$ is the mean plunging velocity, ρ is the density of water, and S is the wing area. As shown in Figure 2.8, the motors, wing models and force sensor were arranged in the same way in the force measurements of hovering and forward flights. With the stroke plane angle pre-defined, the horizontal and vertical forces measured here can be converted to lift and thrust. In hovering flight, the horizontal force acts as lift, by setting the stroke plane at 0° as in Maybury & Lehmann (2004). In forward flight, the horizontal force acts as thrust, by setting the stroke plane at 90° as in Rival *et al.* (2010). The current study did not use exactly same stroke plane angles as the real dragonflies which were measured in previous studies (Norberg, 1975; Wakeling & Ellington, 1997b). Therefore, our model only covers limited aspects of tandem-wing flight. Even so, our work is expected to contribute to the development of MAVs. In chapters 3 and 4, both the hovering and forward flights were investigated. For the convenient comparison between the hovering and forward flights, we estimate the aerodynamic performance using horizontal and vertical forces instead of lift and thrust. In chapter 5, only the hovering flight was studied so that the lift and thrust were used to present the aerodynamic forces.

The aerodynamic power consumption for a pitching and plunging wing over a given period T is defined as,

$$P = \frac{1}{T} \int (F_V \dot{h} + M \dot{\alpha}) dt \quad (2.10)$$

where M is 1/4-chord pitching moment, $\dot{h}$ is the plunging velocity, and $\dot{\alpha}$ is the pitching velocity. Subsequently, the non-dimensional power coefficient is computed as,

$$C_P = \frac{2P}{\rho \overline{U}_P^3 S} \quad (2.11)$$

Since there was no incoming flow in the hovering flight, the mean plunging velocity $\overline{U}_P$ was used as the reference velocity in both hovering and forward flights in the current study to normalize the vertical and horizontal forces, F_V , F_H , as well as the consumed power, P .

In the past studies (Rival *et al.*, 2011a; Heathcote *et al.*, 2004), $\eta = \frac{\overline{F}_T U_\infty}{P}$, where $\overline{F}_T$ was the mean thrust, was used to estimate the propulsive efficiency of forward flight. Here we use the similar efficiency, $\varepsilon = \frac{\overline{F}_H U_\infty}{P}$ in forward flight, but for the hovering flight, the efficiency was defined as $\xi = \frac{\overline{F}_H}{P}$ since there exists no incoming flow.

In the current setup, the forces measured consisted of three components: (i) aerodynamic force, (ii) inertial force and (iii) gravitational force. Similar to other studies (Heathcote *et al.*, 2004; Lua *et al.*, 2010), the inertial and gravitational forces were obtained separately by repeating the same experiment in air, assuming that the aerodynamic forces in air are relatively negligible. Validation of this assumption was carried out on the hind- Wing III model. We replaced the wing model with a small brass rod which was attached to the tip of carbon fiber tube where the wing root was attached. The brass rod had the same mass as the wing model. Since the wing model was less than 5 gram, the brass rod was small enough that its aerodynamic force could be neglected. The comparisons between the hind- Wing III and brass rod are shown in Figure 2.9. The results of F_C and F_N of the wing model and brass rod are almost same proving that the aerodynamic force of the wing model in air is negligible. Therefore in the present study, the net aerodynamic forces produced by the wings in water were obtained by subtracting the inertial and gravitational forces obtained in air from the total forces measured in water.

Following the study on the experimental uncertainty analysis carried out by Coleman & Steele (1995), the uncertainty of force measurements were evaluated

based on the following equation,

$$U_r = \sqrt{B_r^2 + P_r^2} \quad (2.12)$$

where U_r is the experimental uncertainty, B_r and P_r are the bias and precision errors, respectively. The force sensor was precisely calibrated and could be biased every time before the measurements. Therefore, the B_r was evaluated as zero in our study. The P_r is given by

$$P_r = K S_d \quad (2.13)$$

where K is the confidence coefficient and S_d is the sample standard deviation. For sample with number $N \geq 10$, the K equals to 2 for a 95% confidence level. S_d is defined as

$$S_d = \sqrt{\frac{1}{N-1} \sum_{k=1}^N [X_k - \bar{X}]^2}, \quad (2.14)$$

with the mean value defined as

$$\bar{X} = \sqrt{\frac{1}{N} \sum_{k=1}^N X_k}. \quad (2.15)$$

2.5 Phase-locked PIV measurement

Comparing the force traces of the tandem flexible and rigid wings in different situations of both hovering and forward flights, some time instances were identified when remarkable difference between the force traces were observed. Phase-locked particle image velocimetry (PIV) measurements were performed

Figure 2.9: The comparisons between the hind- Wing III and brass rod in F_C and F_N . The "Mass" indicates the brass rod which has same mass as the wing model.

at these time instances to uncover the mechanisms on how the flexibility and phase difference affected the force generation.

As shown in Figure 2.8, a thin laser sheet less than 1mm thick produced by a pair of Nd:YAG lasers with energy of 140 mJ/pulse at wavelength of 532 nm was used to illuminate the flow around the tandem wings at the spanwise location which was $0.5L_{fore}$ far from the wing root. Since the rigid wing models were non-transparent, another set of images were also captured with the laser moved to the opposite side for illumination. In this way, we obtained the full flow field around the rigid wings. In the measurement of rigid tandem wings, a 1024×1024 pixels 12-bit high speed camera (Photron FastCam SA3) with a 50 mm lens was configured perpendicularly to the laser sheet viewing from the bottom (Camera I). However, in the measurement of flexible wing models, the camera view was moved to the top to avoid the large blockage of the laser light due to the bending deformation of the wing models, thus obtaining the information of flow field as much as possible. To capture the flow from the top of the apparatus, a mirror with 45° to the horizontal plane and a camera viewing from front (Camera II) were used. Different from viewing from the top directly, this method allowed the camera to get around the motors. In this setup, the lens

Figure 2.10: The comparisons between the aerodynamic forces obtained by hind- Wing III in 0° -phased tandem-wing cases with and without mirror installed. F_H and F_V are horizontal and vertical forces, respectively.

was replaced with a 105 mm lens. The mirror was immersed into the water and fastened on two aluminium profiles which were fixed on the water tank/tunnel. Two 6 mm wide slots were cut on the mirror to allow the plunging/pitching motion. The slots resulted in some loss of the flow information, but the slots were so narrow that all important features of the flow could be obtained. The effect of the mirror on the force measurements was validated to be negligible by comparing the forces with and without the mirror installed (see Figure 2.10). The flow field was uniformly seeded with polyamid particles (Dantec Dynamics, density: 1.03 g/cm^3) of $20\mu\text{m}$ in diameter.

A total of 250 image pairs were captured for each case to ensure satisfactory convergence in the mean flow field characteristics. An elaboration on estimating the random and bias uncertainties of PIV measured velocities can be found in Wu & Christensen (2006). The random uncertainty in the mean velocities presented in this study is about 0.2% of the maximum velocity in the flow and the bias uncertainty is about 2.5%.

A laser sensor was used to trigger the capturing of images for the PIV measurements. As shown in Figure 2.3, the transmitter and the receiver of the laser sensor were placed on two sides of the motor system. When the

forewing's linear motor was at the beginning of the plunging motion, i.e. $h_{fore} = -h_0$, the laser sent by the transmitter was adjusted to aim at the edge of the connector. So once the linear motor started to move, the laser was immediately received by the receiver and a signal was generated by the laser sensor. In this way, the start of forewing's plunging motion was identified. To carry out the phase-locked PIV measurements at specified time, the signal was sent to a synchronizer (LASERPULSE Model 610036) to generate another signal with time delay set in the synchronizer. Then the delayed signal was used to trigger the PIV system according to the synchronizer to capture the images at the specified time instances.

The PIV images were interrogated using two-frame cross-correlation method in software *Insight 4G*. To improve the resolution and accuracy of the vector fields, two-step iterative interrogation scheme was applied. The relevant parameters were stated in table 2.4. The vector fields were then validated in *Insight 4G* with global and local validations. Around 95% of the the vectors were shown to be valid in our measurements. After the validation, field conditioning procedure was applied. The deleted vectors were replaced by mean value of the neighbourhood vectors within range of 3×3 . Finally, the whole field was low-pass filtered with filter size at 3×3 . The procedures and parameters for the PIV validation were listed in table 2.5.

With the velocity fields obtained, the other flow quantities were computed using Matlab codes. The vorticity of flow is defined as

$$\omega_z = \nabla \times \vec{V}, \quad (2.16)$$

where $\vec{V}$ is the velocity vector. The vorticity can be used directly to identify vortices. However, the shortcoming of this method is that the vorticity is unable to distinguish between swirling and shearing motions. So far, some

Table 2.4: Parameters for the PIV interrogation

Parameters	Value
First iteration ($x \times y$ (pix))	64×64
Second iteration ($x \times y$ (pix))	32×32
Time separation Δt (μs)	1300 $\sim$ 1500
Magnification ($\mu m/\text{pix}$)	≈ 140
$\Delta x/\overline{C}_{fore} = \Delta y/\overline{C}_{fore}$	≈ 0.086
Field of view ($x/\overline{C}_{fore} \times y/\overline{C}_{fore}$)	$\approx 5.5 \times 5.5$
Number of realizations	250

Table 2.5: Parameters for the PIV validation

Procedures and Parameters	Value
Global Validation: allowable vector range (U, V m/s)	5, 5
Local Validation: neighborhood size	3×3
Local Validation: velocity tolerance ($dU = dV$ pix)	2
Field Conditioning: filling holes neighborhood size	3×3
Field Conditioning: smoothing filter size	3×3

methods based on the velocity gradient tensor have been proposed to identify the vortices, e.g. Q-criterion (Hunt *et al.*, 1988), Δ -criterion (Chong *et al.*, 1990), λ_2 -criterion (Jeong & Hussain, 1995) and swirling strength criterion (λ_{ci}) (Zhou *et al.*, 1999). Q-criterion, Δ -criterion, λ_2 -criterion define vortices as regions with 'positive second invariant of $\nabla \vec{V}$ ', 'complex eigenvalues of $\nabla \vec{V}$ ', and 'negative second largest eigenvalue of the pressure Hessian', respectively. In planar flows, these three conditions are equivalent (Jeong & Hussain, 1995). The swirling strength defines the vortices using 'imaginary part of the complex eigenvalues of $\nabla \vec{V}$ '. This method is developed based on the Δ -criterion. In Ren & Wu (2011), the correlation between swirling strength (λ_{ci}) and vorticity (ω_z), i.e. $R_{\lambda\omega} = \lambda_{ci} \times \omega_z$ was used to identify the vortices, which has been proven to be able to truly identify the rotational cores of vortices from two-dimensional PIV measurements with significantly improved signal-to-noise

ratio. Comparing with the other methods introduced above, the $R_{\lambda\omega}$ not only reveal the rotational sense of vortices, but also enhance the signal to noise ratio. In the present study, the vorticity fields were compared with the $R_{\lambda\omega}$ fields. Similar results were obtained by these two methods, which indicated that the vorticity fields were enough in the current flow to truly identify the rotational cores of vortices. Therefore, the vorticity fields were chosen to be presented in the following results and discussions for convenience.

2.6 Time-resolved PIV measurement

To further investigate the dynamics of the force generation, the time-resolved particle image velocimetry (TR-PIV) measurements were carried out to measure the dynamics of flow fields through the whole cycle in the hovering flight at $f = 1Hz$. Three spanwise locations which were $0.25L_{fore}$, $0.5L_{fore}$ and $0.75L_{fore}$ away from the wing root were measured. Flexible and rigid wings in single-wing and tandem-wing configurations at $\Psi = 0^\circ$, 90° and 180° were all investigated. The setup of the measurements was similar to that of phase-locked PIV measurements. But the laser was replaced by a Nd:YLF laser (527 nm, 12 mJ/pulse at 250 Hz). The signal sent by the laser sensor at the start of the forewing's plunging motion was used to generate 250 triggering signals at frequency of 250 Hz on the synchronizer. Each triggering signal was then sent to the camera to trigger the image capturing. Therefore, the cameras recorded images at a rate of 250 image pairs per second, i.e. the flow fields at 250 locations were measured within a cycle. 250 cycles were recorded to satisfy the convergence in the mean flow field characteristics at each position. The parameters for the PIV measurements were set in *Insight 4G* as shown in Figure 2.11. The flow fields were also processed and validated in *Insight 4G* with the

Figure 2.11: Snapshot of the parameters set in *Insight 4G*

parameters stated in table 2.4 and 2.5.

In the present study, the flows around the wing models are three-dimensional. 3D tomographic PIV measurements or 2D PIV measurements along two orthogonal measurement planes are expected. However, 2D PIV measurements at different spanwise locations were chosen for the investigation due to the following reasons: 1) The span lengths of wing models are about 120 mm. However, the maximum volume thickness of the 3D tomo-PIV measurement is only 8 mm, which is too thin for the wing models; 2) If the wing models are scaled down to meet the size limitation of 3D tomo-PIV measurement, the aerodynamic forces would not be large enough for a reasonable force measurement, even though a very accurate force sensor (ATI nano 17, accuracy: 3 mN) was employed; 3) The results of force measurements showed that the flexible and rigid tandem wings had significantly different force dynamics, which required for further investigation by measuring time-resolved flow fields. However, unlike time-resolved PIV, the tomographic PIV measurement is not fast enough to capture the dynamic performance of the flow fields; 4) Moreover, there are

Figure 2.12: Setup for the deformation measurements.

also many previous studies on the dragonflies demonstrating that the spanwise flow is not dominant feature, such as Thomas *et al.* (2004), Lu *et al.* (2007) and Rival *et al.* (2011b). In the current study, since the wing models were undergoing plunging and pitching motions, the chordwise flow was expected to be much more significant than the spanwise flow. Therefore, keeping the limitations of the 2D measurements in mind, the present study focused on the 2D flow fields at different spanwise locations to capture some major flow field features of the forewing-hindwing interactions.

2.7 Deformation measurement

To relate the deformations of wing models to the force generations, 2D and 3D locations of the wing models were measured. In chapter 4, laser sheets at low power were used to illuminate the wing models at the same spanwise locations as in the PIV measurements. The laser sheets appeared as lines on the wings which showed the 2D locations of the wing models. Comparing the 2D locations of

the flexible wings with those of the rigid wings, 2D deformations of the flexible wings were obtained. In chapter 5, the 3D locations of wing models during motion were reconstructed using direct linear transformation (DLT) technique following the studies of Abdel-Aziz & Karara (1971) and Koehler *et al.* (2012). The DLT algorithm can be expressed as the following two equations,

$$u + \Delta u = \frac{L_1x + L_2y + L_3z + L_4}{L_9x + L_{10}y + L_{11}z + 1}, \quad (2.17)$$

$$v + \Delta v = \frac{L_5x + L_6y + L_7z + L_8}{L_9x + L_{10}y + L_{11}z + 1}, \quad (2.18)$$

where the constants L_1 to L_{11} are the DLT parameters, u and v are the image coordinates, x , y and z are the spatial coordinates of object, and Δu and Δv are the optical errors, which can be expressed as

$$\Delta u = \zeta(L_{12}r^2 + L_{13}r^4 + L_{14}r^6) + L_{15}(r^2 + 2\zeta^2) + L_{16}\zeta\kappa, \quad (2.19)$$

$$\Delta v = \kappa(L_{12}r^2 + L_{13}r^4 + L_{14}r^6) + L_{15}\kappa\zeta + L_{16}(r^2 + 2\kappa^2), \quad (2.20)$$

where

$$[\zeta, \kappa] = [u - u_0, v - v_0], \quad (2.21)$$

$$r^2 = \zeta^2 + \kappa^2. \quad (2.22)$$

Parameters L_{12} to L_{14} are the optical distortion terms, while L_{15} and L_{16} are the de-centering distortion terms. The projection point's coordinate is indicated as $[u_0, v_0]$. However, the optical errors are usually not considerable and can be ignored. Therefore, the eqn 2.17 and 2.18 can be reduced to be

$$L_1x_i + L_2y_i + L_3z_i + L_4 - u_iL_9x_i - u_iL_{10}y_i - u_iL_{11}z_i = u_i, \quad (2.23)$$

$$L_5x_i + L_6y_i + L_7z_i + L_8 - v_iL_9x_i - v_iL_{10}y_i - v_iL_{11}z_i = v_i. \quad (2.24)$$

With calibration, the DLT parameters L_1 to L_{11} can be obtained. Images of calibration marks with known spatial coordinates need to be taken to obtain their image coordinates. All the image and spatial coordinates of the marks (N points) recorded are then plugged in equations 2.23 and 2.24 to form a matrix equation:

$$AL = b, \quad (2.25)$$

where A is a $2N \times 11$ matrix, $L = (L_1, \dots, L_{11})^T$, and b is a $2N$ -vector. By solving the matrix equation, the 11 DLT parameters can be determined.

In the reconstruction of spatial coordinates, only the image coordinates are known. At this step, the equations 2.23 and 2.24 can be re-arranged as,

$$(L_1 - u_i L_9)x + (L_2 - u_i L_{10})y + (L_3 - u_i L_{11})z = u_i - L_4, \quad (2.26)$$

$$(L_5 - v_i L_9)x + (L_6 - v_i L_{10})y + (L_7 - v_i L_{11})z = v_i - L_8. \quad (2.27)$$

Plugging in the image coordinates recorded by two cameras, the equations formed another matrix equation:

$$TX = d, \quad (2.28)$$

where T is a 4×3 matrix, $X = (x, y, z)^T$, and d is a 4-vector. The solution of this matrix equation was the reconstructed spatial coordinates.

As shown in Figure 2.12, the forewing and hindwing were marked with 160 and 192 black dots with a diameter of 1.6 mm evenly. Firstly, the image locations of the marks on the wings during motion were recorded by two 12-bit 1024×1024 high speed cameras (Photron FastCam SA3) at a frame rate of 125 Hz. The cameras were configured in the same vertical line, with angle

between two cameras at about 30° . Then a calibration procedure was carried out. In the calibration, images of a calibration target shown in Figure 2.12 were taken with the calibration target translated at an interval of 5 mm along the plunging direction and a total range of 100 mm. The range of the target used for calibration was about $140\text{mm} \times 140\text{mm}$, with interval between two marks of 15 mm. With the DLT parameters obtained by the calibration, the image positions of the marks on the wing models recorded by the cameras were then used to reconstruct the actual locations on the moving wings. The accuracy of the 3D reconstruction was ± 0.3 mm in the plunging direction, while ± 0.05 mm in the other two directions. By comparing the 3D locations of flexible and rigid wings, the 3D deformations of flexible wing models were obtained.

Chapter 3

Forewing-hindwing interactions of rigid tandem wings in hovering and forward flights

This chapter presents the study on the forewing-hindwing interactions of rigid tandem wings undergoing combined plunging/pitching motion in hovering flight ($Re_{\overline{U}_P} = \frac{\overline{U}_P \overline{C}_{fore}}{\nu} = 4,544$) and in forward flight ($Re_{U_\infty} = \frac{U_\infty \overline{C}_{fore}}{\nu} = 3,873$, $St=0.6$). The aerodynamic performance of rigid tandem wings has been investigated widely in either hovering or forward flight. However, the previous studies seem to draw mixed conclusions on whether the interactions are beneficial to the aerodynamic performance of tandem-wing flight when compared with the single-wing flight (see Table 3.1). The most favorable phase differences obtained in previous studies were not consistent either (see Table 3.1). Moreover, the mechanisms of the forewing-hindwing interactions which affected the aerodynamic forces were also found to be diverse between studies. These different results could be attributed to the differences in flow parameters of Re and St , and in wing models and motion. As such, much more studies are needed to fill the wide gaps in the parameter spaces. For example, in most previous studies for the forward flight (Rival *et al.*, 2010, 2011a; Lee, 2011; Broering *et al.*, 2012), Re_{U_∞} was on the order of 10^4 , which was much higher than that of real dragonflies (Rüppell, 1989; Wakeling & Ellington, 1997b,a), i.e. order of 10^3 . Therefore, the Reynolds numbers $Re_{\overline{U}_P}$ and Re_{U_∞} employed in current study are set to be similar to those of real dragonflies. The force and phase-locked PIV measurements are carried out in both hovering and forward flights to check 1) whether the tandem wings can outperform the single wing in current

study; 2) how the phase differences will affect the aerodynamic performance in hovering and forward flights with same motion kinematics; 3) what the flow structures underlining the forewing-hindwing interactions are in the conditions of the current study. In addition, few past studies have compared the hovering and forward flights to investigate how the incoming flow might change the interaction between forewing and hindwing. The effect of incoming flow will also be discussed in this study.

Table 3.1: Summary of previous studies

Tandem wings better?	Flight	Studies	Method	Wing motion	Wing model	Ψ studied	Parameters	Best Ψ
Yes	Hovering	Lan & Sun (2001)	2D Num	plunging & pitching	elliptical airfoils	$0^\circ, 90^\circ, 180^\circ$	$Re_{U_W} = C\bar{U}_{P_{max}}/\nu = 1000$	$C_L: 0^\circ$ $C_T: 90^\circ$
		Hsieh et al. (2010)	2D Num	plunging & pitching	elliptical airfoils	$0^\circ, 90^\circ, 180^\circ$	$Re_W = C\bar{U}_{P_{max}}/\nu = 625$	$C_L: 0^\circ$ $C_T: 90^\circ$
No	Hovering	Maybury & Lehmann (2004)	3D Exp: flow visualization and PIV	flapping with constant AOA	flat plates with planform of real wings	$-180^\circ \sim 180^\circ$	$Re_W = C\bar{U}_{tip}/\nu \approx 100$	$C_L: 0^\circ$
		Sun & Lan (2004)	3D Num	flapping & pitching	flat plates with planform of real wings	180°	$Re_W = 2n\Theta r_2 C/\nu = 1350$	
		Lu et al. (2007)	3D Exp: flow visualization	flapping & pitching	wing models with AR of real wings	$0^\circ, 90^\circ, 180^\circ$	$Re_W = 2n\Theta RC/\nu = 1569$	
		Rival et al. (2011)	2D Exp: PIV	plunging & pitching	SD7003 airfoils	$0^\circ \sim 360^\circ$	$Re_{U_W} = C\bar{U}_{P_{max}}/\nu = 3000$	$C_L: 90^\circ$
	Forward	Wang & Sun (2005)	3D Num	flapping & pitching	flat plates with planform of real wings	$0^\circ, 60^\circ, 90^\circ, 180^\circ$	$Re_\infty = C\bar{U}_\infty/\nu = 333-1663$ $J = U_\infty/2n\Theta RC = 0-0.75$ $St = n\Theta RC/U_\infty = 0.67-3.3$	C_L : varied at different J $C_T: 60^\circ$
		Rival et al. (2010)	2D Exp: PIV	forewing: plunging; hindwing: fixed	SD7003 airfoils		$Re_\infty = C\bar{U}_\infty/\nu = 30000$ $k = \pi f C/U_\infty = 0.25$ $St = 2fh_0/U_\infty = 0.125$	
		Rival et al. (2011)	2D Exp: PIV	plunging & pitching	SD7003 airfoils	$0^\circ, 30^\circ, 60^\circ, 90^\circ, 120^\circ$	$Re_\infty = C\bar{U}_\infty/\nu = 30000$ $k = \pi f C/U_\infty = 0.25$ $St = 2fh_0/U_\infty = 0.125$	$C_T: 90^\circ$
		Lee (2011)	2D Exp: PIV	pitching	NACA 0012 airfoils	$0^\circ, 180^\circ$	$Re_\infty = C\bar{U}_\infty/\nu = 85000$	$C_L: 180^\circ$
		Broering et al. (2012)	2D Num	plunging & pitching	NACA 0012 airfoils	$0^\circ, 90^\circ, 180^\circ$	$Re_\infty = C\bar{U}_\infty/\nu = 10000$ $St = 2fh_0/U_\infty = 0.3$	$C_L: 0^\circ$ $C_T: 0^\circ$

Figure 3.1: Average horizontal force coefficients C_H for hovering and forward flights in various cases: (i) combined performance of both wings; (ii) forewings; and (iii) hindwings. The black solid line and red dash line in (i) indicate the C_H of single hindwing in hovering and forward flights, respectively.

3.1 Results and discussions

3.1.1 Force measurements

Figure 3.1 showed the average horizontal force coefficients C_H for both hovering and forward flights at all three difference phase angles for (i) combined performance of tandem wings; (ii) forewings; and (iii) hindwings. The C_H of forewing and hindwing operated in isolation were also included in Figure 3.1 (ii) and (iii) as references. Because the forewing and hindwing have different wing planforms, the resulted C_H for them in isolation are a bit different. Since the average vertical force coefficients were measured close to zero for all the cases studied due to the nearly symmetric vertical force distribution within a stroke cycle, they were not discussed further hereinafter.

As shown in Figure 3.1(i), C_H decreased monotonically from $\Psi = 0^\circ$ to 180° in the hovering flight. However, in the forward flight, tandem wings obtained highest C_H at 90° while lowest C_H at 180° . Note that the horizontal force measured here acts as the lift in the hovering flight while as the thrust in the forward flight. These results concerning the most favorable phase differences are consistent with some other studies (Lan & Sun, 2001a; Hsieh *et al.*, 2010; Maybury & Lehmann, 2004; Rival *et al.*, 2010), although at different parameters

of Re and St and with different wing kinematics.

In hovering flight, Figure 3.1(ii) showed that 0° led to significantly higher C_H than the other two phases on the forewing, and Figure 3.1(iii) showed that, on the hindwing, C_H value at 0° is only slightly higher than that at 90° but C_H at 180° is much lower than the other two phases. In addition, at $\Psi = 0^\circ$, due to the existence of the other wing, the forewing and hindwing in tandem-wing configuration achieved 25.9% and 12.5% higher C_H values, respectively, than when they were operated in isolation. It was also observed from Figure 3.1(ii) and (iii) that the general trends of C_H values with phases are the same on forewing and hindwing: they are both monotonically decreasing with higher phases. As such, both forewing and hindwing contributed to the decreasing C_H from 0° to 180° for the tandem wings in the hovering flight.

In forward flight, Figure 3.1(ii) and (iii) illustrated that the forewing obtained highest C_H at 0° while the hindwing achieved highest one at 90° . Although the forewing at $\Psi = 90^\circ$ produced lower C_H than at 0° , the hindwing obtained significantly higher C_H at 90° , which is the reason to render a net increase of C_H for tandem wings from $\Psi = 0^\circ$ to 90° .

To check if the tandem wings could outperform the single wing, the hindwing operated in isolation was chosen as the reference since it obtained larger C_H than the single forewing in either hovering or forward flight. The comparison shown in Figure 3.1(i) revealed that at $\Psi = 0^\circ$ C_H of tandem wings in both hovering and forward flights are larger than the single wing; at $\Psi = 90^\circ$ C_H of tandem wings is comparable to that of single wing in the hovering but is much higher in the forward flight; however at $\Psi = 180^\circ$, tandem wings are worse than the single wing for both flights.

In contrast, no phase difference was found at which tandem wings produced larger forces than the single wing in Rival *et al.* (2011b) for the hovering flight

and in Broering *et al.* (2012) for the forward flight, although these two studies had similar wing kinematics as the current study. Both studies used two-dimensional wing models which were different from our 3D one. However, past studies (Rival *et al.*, 2011b; Lu *et al.*, 2007; Thomas *et al.*, 2004) showed that the spanwise flow was not dominant feature, which indicated that there was no dramatic differences between 2D and 3D models. The only difference in motion kinematics between the current study and Rival *et al.* (2011b) is the amplitude of the plunging motion of the wings. The plunging amplitude in Rival *et al.* is 0.5 chord length while that in our study is 1.5 chord length. Therefore, the plunging amplitude seems important in tandem wings in the hovering flight at phases less than 90° . In the study of Broering *et al.* for the forward flight, their different results at $\Psi = 0^\circ$ and 90° could come not only from the smaller plunging amplitude (0.5 chord), but also possibly mainly from the differences in the two important parameters of Re and St.

Comparing C_H between hovering and forward flight at each phase angle could reveal the effects of the incoming flow given the same wing kinematics. Figure 3.1 showed that the incoming flow lowered C_H for all the phases, probably due to the higher drag, which indicates that in order to produce higher C_H for the same tandem wings in the forward flight the wing motions need to change from those in the hovering flight. In addition, compared to all the other cases, the hindwing at $\Psi = 90^\circ$ was found to be least affected by the incoming flow.

The dynamic variations of the horizontal force coefficients within a stroke cycle were presented in Figure 3.2. Dramatic differences could be observed between the wings in tandem-wing configuration and in isolation, highlighting the strong wing-wing interactions. The tandem wings showed advantages over the single wing mainly due to the much higher peaks, such as that of the hindwing at $\Psi = 0^\circ$ in hovering flight and that of the hindwing at $\Psi = 90^\circ$ in forward flight.

Figure 3.2: Time histories of horizontal force coefficients obtained by forewing and hindwing in single-wing, and tandem-wing configurations with phase differences of $\Psi=0^\circ$, 90° and 180° in hovering and forward flights. The white backgrounds represent the up-strokes, while the grey backgrounds represent the down-strokes. Acceleration and deceleration periods are the first and second half of the up- and downstrokes, respectively.

Another important reason was the lag between the force traces, such as the lag between the force traces of single and 0° -phased hindwings in the forward flight during the acceleration periods. Time instances (i) to (iv) in hovering flight and time instances (i) to (iv) in forward flight, where significant differences were observed in the instantaneous C_H , were chosen to perform further PIV investigation to uncover the mechanisms of forewing-hindwing interactions.

3.1.2 PIV measurements

Hovering flight

Figure 3.3 presented the average velocity and vorticity fields of tandem wings at $\Psi=0^\circ$, 90° and 180° , with those of single wing as references, in hovering flight at the selected time instances marked in Figure 3.2. For the forewings, time instances (i) $(t/T)_F = 0.12$ and (ii) $(t/T)_F = 0.296$ were chosen to study how the horizontal force on the forewing was affected by the wing-wing interactions.

At time instance (i) $(t/T)_F = 0.12$, Figure 3.2 showed that all four cases (tandem wings at 0° , 90° , 180° and single wing) obtained kinks on the force traces, and the 0° - and 90° -phased cases generated the highest and lowest C_H , respectively. The flow fields shown in Figure 3.3(i) revealed that strong LEVs and TEVs were generated on the ventral (lower) surfaces of the forewings for all cases. These LEVs and TEVs produced low pressure regions in their core, which was the main reason to account for the significant forces (Liu *et al.*, 1998; Aono & Liu, 2013). Compared to that in the single-wing case, the downwash flow behind the forewing in tandem-wing configuration at $\Psi=0^\circ$ was enhanced due to the blockage of the hindwing. In contrast, it was weaker and induced toward horizontal direction by the larger LEV on the hindwing in the 90° -phased case. Although the LEVs of the forewing appeared too far to be affected by the

Figure 3.3. (i) to (ii)

Figure 3.3: Average velocity and vorticity fields for tandem wings at $\Psi=0^\circ$, 90° and 180° and for the single wing at (i) $(t/T)_F = 0.12$, (ii) $(t/T)_F = 0.296$, (iii) $(t/T)_H = 0.268$ and (iv) $(t/T)_H = 0.832$ in the hovering flight. The regions with black borders were obtained with laser illuminating from the opposite side.

hindwing, the TEVs were found to be directly modified by the downwash flow which itself was altered by the hindwing at different locations. The variation of the spatial characteristics of the TEVs, such as the size, strength and relative locations on the forewing, then resulted in different forces at various phases.

At time instance (ii)(t/T)_F = 0.296, the forewing at $\Psi = 180^\circ$ generated remarkably lower C_H than the other cases (see Figure 3.2). As shown in Figure 3.3(ii), the clockwise LEV on the hindwing induced upwards flow on the right side of the forewing at $\Psi=180^\circ$, which was different from the other cases where the flow went downwards. The upwards flow led to the weakest TEV, resulting in the dramatically lower C_H at $\Psi = 180^\circ$. The enhancement on the strength of forewing's downwash flow at $\Psi = 0^\circ$ was also observed at this time instance. But there was little difference in the directions of forewing's downwash flows between $\Psi = 0^\circ$ and $\Psi = 90^\circ$. Therefore, the differences in the strengths of TEVs on forewings were not observed very significant among single-wing, 0° -phased and 90° -phased tandem-wing cases.

For the hindwings, time instances (iii)(t/T)_H = 0.268 and (iv)(t/T)_H = 0.832 were investigated. As described below, the forewings modified the strength of LEVs on the hindwings with different downwash flows. The existence of forewings also made the LEVs closer to the hindwings. The changes in LEVs then further caused the modifications in the strengths of TEVs on the hindwings. The change in the location of LEV on the hindwing did not appear to have been identified as one of the reasons to cause the force variations in previous studies.

At the upstroke peak position of hindwings, i.e. at time instance (iii)(t/T)_H = 0.268, the largest force was obtained at $\Psi = 0^\circ$ while the smallest one was at $\Psi = 180^\circ$. Figure 3.3(iii) revealed that the forewings induced different flows and thus affected the LEVs of the hindwings. At $\Psi = 0^\circ$, a strong downwash

flow was induced by the forewing due to the blockage of the hindwing. The enhanced downwash flow in turn induced a stronger LEV on the hindwing. In addition, it made the LEV closer to the hindwing when compared with the single-wing case. The modifications in strength and location both enhanced the low-pressure region on the ventral surface. Further, as the LEV became closer to the hindwing, the spacing between the LEV and TEV decreased. The enhanced LEV then increased the strength of the TEV. These favourable characteristics of the LEV and TEV mainly account for the highest force peak of the hindwing at $\Psi = 0^\circ$. At $\Psi = 90^\circ$, the flow on the left side of hindwing was almost vertically downwards. This flow contributed to the stronger LEV on the hindwing than that of the single-wing case. In 180° -phased case, the forewing plunged in the opposite direction of hindwing. The forewing generated a downwards and rightwards flow at the ventral side of hindwing, which forced the LEV of hindwing to fully attach on the wing model. Nevertheless, since the LEV was so weak, the lowest value of C_H was produced for the 180° -phased case.

At time instance (iv) $(t/T)_H = 0.832$, similar to the situation at time instance (iii), the existence of forewings induced flows which enhanced the LEVs on the hindwings at $\Psi=0^\circ$ and 90° compared to the single hindwing case. Moreover, stronger TEV was induced on the hindwing of 0° -phased case. At $\Psi=180^\circ$, the TEV of forewing was located above the LEV of hindwing and they had the same rotational directions. The flow induced by the TEV of forewing thus showed detrimental effect on the strength of the LEV on the hindwing. The interactions of these two vortices also made the LEV closer to the hindwing. However, the much weaker LEV and TEV resulted in the lowest horizontal force on the hindwing for the 180° -phased case.

At both time instances (iii) and (iv), the hindwings in 90° - and 180° -phased

cases obtained multiple-core LEVs, while the corresponding single hindwings generated single-core LEVs each of which was followed by a shed vortex (see Figure 3.3(iii) and (iv)). It therefore appeared that the forewings restrained the shedding of the LEVs on the hindwings. Note that the shedding behavior of LEV is similar to the continuous von Karman shedding behavior which presents a repeating pattern of swirling vortices. Instead of directly detaching from the wing model, a new LEV was generated while the old one was being shed. However, although the tendency for vortices to attach to the wing is a beneficial factor for force generation, the resultant force could be influenced by quite a few other factors.

At each time instance, the modifications in strengths of LEVs and TEVs are significant among cases with different phase differences. This was mainly caused by the different forewing-hindwing interactions. As shown in Figure 3.3, the forewing-hindwing interactions induced LEVs or TEVs with different strengths by modifying the flows between the forewing and hindwing in both strength and direction. For example, the flows between 0° -phased tandem wings at time instances (i) and (iii) were greatly enhanced by the forewing-hindwing interactions as compared to other cases. With the enhanced flows, stronger TEV and LEV were generated on the forewing at time instance (i) and on the hindwing at time instance (iii), respectively, which then further induced stronger forewing LEV and stronger hindwing TEV, respectively.

Forward flight

In Figure 3.4, the average velocity and vortices fields in the forward flight were presented for the single and tandem wings at $\Psi=0^\circ$, 90° and 180° , at time instances (i) $(t/T)_F = 0.287$, (ii) $(t/T)_H = 0.08$, (iii) $(t/T)_H = 0.272$ and (iv) $(t/T)_H = 0.832$. Time instance (i) $(t/T)_F = 0.287$ was chosen for the

Figure 3.4. (i) to (ii)

Figure 3.4: Average velocity and vorticity fields for tandem wings at $\Psi=0^\circ$, 90° and 180° and for the single wing at (i) $(t/T)_F = 0.287$, (ii) $(t/T)_H = 0.08$, (iii) $(t/T)_H = 0.272$ and (iv) $(t/T)_H = 0.832$ in the forward flight. The regions with black border were obtained with laser illuminating from the opposite side.

forewings since the 180° -phased case obtained much lower C_H than the other cases. As shown in Figure 3.4(i), due to the existence of the incoming flow, the downwash flows for the single-wing, tandem wings at 0° and 90° are quite similar. Therefore, the hindwings exerted weak effects on the forewings' downwash flows, and thus on the strength of the TEV on forewing for these cases. In contrast, at $\Psi = 180^\circ$, the TEV of the forewing rode on the LEV of the hindwing, enlarging the low-pressure region near the trailing edge of the forewing. As a result, additional negative horizontal force was produced, leading to the extremely low positive horizontal force on the forewing at $\Psi=180^\circ$.

From the dynamic force traces shown in Figure 3.2, it is obvious that in the forward flight, the hindwing was much more affected by the forewing than vice versa. Therefore the rest of time instances for examination of the flow fields were chosen for the hindwings. At time instance (ii) $(t/T)_H = 0.08$, Figure 3.4(ii) showed that only the 0° -phased case had a strong LEV on the ventral side of the hindwings which should mainly account for the highest C_H at this phase. Compared to the single-wing case, it was found that this LEV was induced by the large vortex on the forewing. Similar flows were also observed in the study of Rival *et al.* (2010). Instead of LEVs on the ventral side, the 90° and 180° -phased cases had vortices on the dorsal (upper) side as in the single hindwing case. These vortices were the LEVs of hindwings in the previous downstroke. As the hindwings reversed the plunging direction, these vortices fell on the dorsal side. Differences of these dorsal vortices could be observed and they were caused by the various locations of the forewings at different phases.

At time instance (iii) $(t/T)_H = 0.272$, the hindwing at 90° -phased case generated extremely higher peak value than the other cases. As shown in Figure 3.4(iii), a large vortex lay on the forewing at 90° . This large vortex induced a strong downwash flow on its right side which then enhanced the LEV on

the hindwing compared to the single-wing case. However, the flows induced by the forewings at $\Psi = 0^\circ$ and 180° were weaker than the 90° case. In addition, at $\Psi = 0^\circ$ and 180° , the induced flows by the forewings were almost horizontal, which adversely affected the strengths of the LEVs on the hindwings and eventually led to the much lower peaks than the 90° case.

When the hindwing moved to the instance (iv) $(t/T)_H = 0.832$, it produced a large peak of C_H at $\Psi = 180^\circ$ which was comparable to that at 90° . From Figure 3.4(iv), it could be seen that the hindwing at $\Psi = 180^\circ$ took the TEV of forewing and carried the vortex on the dorsal side, which then enhanced the low pressure on the dorsal side of the hindwing to produce a remarkable increase of the positive horizontal force. This interaction was also observed by Lan & Sun (2001*a*). For the 90° -phased case, the strong upwash flow and the large vortex above the hindwing accounted for the high C_H value of the hindwing.

Comparison between hovering and forward flight

It was indicated from the above results that the wing-wing interactions were different with or without the incoming flow. Therefore in this section two comparisons were made between the hovering and forward flights at almost the same time instances within a stroke cycle to illustrate the effects of the incoming flow on the flow structures around the tandem wings. To the authors' knowledge, such a comparison under the same wing kinematics and flow parameters was not made in the past.

First, the time instance of (iii) $(t/T)_H = 0.268$ of the hovering flight was chosen to compare with (iii) $(t/T)_H = 0.272$ of the forward flight. At this time instance, the locations of the hindwings of both flights reached their respective upstroke peaks. However, the hindwing produced the highest C_H values at $\Psi =$

0° in the hovering flight while at 90° in the forward flight. It could be observed after comparing Figure 3.3(iii) and Figure 3.4(iii) that although the vortical structures were generally similar between these two flights, their locations were shifted further downstream in the forward flight due to the existence of the incoming flow. For instance, at the phase angle of 90° , the LEV on the forewing was shifted from near the leading edge in the hovering flight to the forewing's center in the forward flight. The shifted LEV on the forewing induced a stronger downwash flow which in turn enhanced the LEV on the hindwing in the forward flight.

Another effect of the incoming flow in the forward flight was found to modify the induced flow behind the forewing, which could then change the size or strength of the LEV on the hindwing. For example, at $\Psi = 0^\circ$, the direction of the downwash flow induced by the forewing was changed due to the existence of the incoming flow, which was observed detrimental to the LEV on the hindwings and as a result much lower C_H value in the forward flight was obtained than in the hovering flight.

The second comparison was done at exactly the same time instances of (iv) $(t/T)_H = 0.832$ of these two flights. Here, Figure 3.2 showed that the wing-wing interactions exerted adverse effect in the hovering flight but very beneficial effect in the forward flight on the hindwing at the same phase angle of 180° . The flow fields revealed that since the TEV of the forewing was shifted further downstream, it was caught by the hindwing to connect with the LEV of the hindwing. Another example is at $\Psi = 90^\circ$ at this time instance. The LEV on the forewing as shifted to the wing's center by the incoming flow and the induced flow enhanced the LEV of the hindwing, which was the reason for the second peak value of C_H .

3.2 Summary and conclusions

In this chapter, rigid tandem wings undergoing combined plunging/pitching motion in hovering flight at $Re_{\overline{U}_p}$ of 4,544, and in forward flight at Re_{U_∞} of 3,873 with Strouhal numbers of 0.6, were investigated with force and phase-locked PIV measurements. Three phase differences of $\Psi=0^\circ$, 90° , and 180° between the forewing and hindwing were studied, with wings operating in isolation as the reference. The average horizontal force coefficients measured in this study showed that (1) at $\Psi = 0^\circ$, tandem wings outperformed single wings in both hovering and forward flights; (2) at $\Psi = 90^\circ$, tandem wings produced comparable forces to the single wing in hovering flight, but much higher forces in the forward flight; (3) at $\Psi = 180^\circ$, tandem wings were worse in both flights. These results are in contrast with some past studies (Rival *et al.*, 2011*b*; Broering *et al.*, 2012), even with very similar wing kinematics, which showed that tandem wings produced less forces at all phase angles. However, the conflicting results could be explained by the different flow parameters such as Re and St and minute differences in wing motions. It is therefore suggested that the regime might abruptly transit from “tandem wings better than single ones” to “tandem wings worse than single ones” within a quite narrow parameter space of flows and wing kinematics. More studies are of course needed to verify this hypothesis.

From the velocity and vorticity fields measured by phase-locked PIV at a few selected time instances at which large instantaneous forces differences occurred, it was found that generally the wing-wing interactions were realized through the modifications of the characteristics of the LEV and TEV of the wings. This mechanism is inline with many other past studies. A comparison made between the hovering and forward flight revealed that the effects of the incoming flow include moving the LEV and TEV further downstream and changing the flow

between the wings.

Chapter 4

Force measurements of flexible tandem wings in hovering and forward flight

As introduced in 'Chapter 1. Introduction', the earlier studies are mostly concerned with the effects of either tandem arrangement or wing flexibility only. The combined effect of tandem arrangement and wing flexibility on the aerodynamic performance was hardly studied. This chapter aims to fill this gap by investigating the aerodynamic performance of flexible tandem wings. Three sets of flexible wing models, i.e. Wing I, Wing II and Wing III, were investigated with a set of rigid wing models as the reference. Force, 2D deformation and phase-locked PIV measurements were performed in a hovering flight ($Re_{\overline{U}_p} = 4,544$) and forward flights at $f = 1Hz$ ($Re_{\overline{U}_p} = 4,544$ and $St = 0.6$) and $f = 0.5Hz$ ($Re_{\overline{U}_p} = 2,272$ and $St = 0.3$). The average force coefficients, power consumption and efficiency, as well as the force traces of the flexible tandem wings were compared with those of rigid tandem wings to study the effects of wing flexibility on the aerodynamic performance of tandem wings. Measurements were carried out at different phase differences at $\Psi = 0^\circ, 90^\circ$ and 180° to investigate the effect of phase difference. By comparing the force traces of flexible and rigid wing models, the factors accounting for the difference in the average horizontal forces of flexible and rigid wing models can be identified. By analysing the flow fields obtained by the phase-locked PIV measurements, the mechanisms of how the wing flexibility leads to the significant differences between the force traces of the flexible and tandem wings can be revealed.

4.1 Results and discussions

4.1.1 Hovering flight

Figure 4.1 shows the average horizontal force coefficient C_H , power coefficient C_P , and efficiency ξ of tandem wings for different wing models at the three phase differences of $\Psi=0^\circ$, 90° and 180° in the hovering flight. For both rigid and flexible tandem wings in all cases, the average vertical force coefficients, C_V , are close to zero due to the nearly symmetric distribution of the instantaneous vertical force within a stroke cycle. Therefore, the vertical force coefficients will not be further discussed here.

Figure 4.1 (a) shows that tandem Wing III models obtained the highest horizontal force coefficients, C_H , in each phase difference studied. Compared with the tandem rigid wings, C_H of Wing III is 17.7%, 5.9%, and 19.4% higher at phase differences of 0° , 90° , and 180° , respectively. However, the more flexible tandem Wing II models achieved lower horizontal force coefficients at $\Psi=90^\circ$, albeit only slightly higher C_H values at $\Psi=0^\circ$ and 180° than the rigid ones. The most flexible Wing I models used in the current study produced the least C_H which is significantly lower than the other wings. These results indicated that only an appropriate amount of flexibility in the tandem wings could produce noticeably higher horizontal force coefficients than the rigid counterparts. Another observation from Figure 4.1 (a) is that, except for Wing I models which generated about the same C_H at all three phase differences, C_H values for the other wings decrease from $\Psi=0^\circ$ to 180° . This trend of horizontal force coefficient with phase differences in hovering flight is consistent with some past studies (Alexander, 1984; Wakeling & Ellington, 1997b). If Wing I models are excluded from considerations since they generated much lower C_H as compared with the rest, Figure 4.1 (a) illustrates that the tandem Wing III at $\Psi=0^\circ$ produced the high-

Figure 4.1: (a) Average horizontal force coefficient C_H , (b) power coefficient C_P , and (c) efficiency ξ of tandem wings for different wing models in the hovering flight.

est horizontal force coefficient while the tandem rigid wings at $\Psi=180^\circ$ produced the lowest.

On the other hand, the power coefficients illustrated in Figure 4.1 (b) show that the higher aerodynamic force is produced at the expense of higher power consumed, since the trend of C_p is very similar to that of C_H . As a result, the efficiencies shown in Figure 4.1 (c) show much smaller difference than force and power coefficients. In particular, although tandem Wing III models generate much higher horizontal forces than the rigid tandem wings, their efficiencies are almost the same, because more powers are consumed by the flexible Wing III models.

The aerodynamic performance of all wing models used in the current study, including both forewings and hindwings of various flexibilities, operating in isolation were also measured, in order to make a comparison between tandem and single wings. The hind- Wing III wing performed best in single-wing situation with the highest C_H of 1.94 and ξ of 2.06. As the best pair in tandem wings, the tandem Wing III models show advantage in 0° -phased situation with 11.7% larger C_H . However, they show disadvantage in both 90° -phased and 180° -phased situations with 9.0% and 18.2% lower C_H , respectively. In addition, the efficiency, ξ , of tandem Wing III models in all phase angles are slightly (about 5%) lower than that of the single hind- Wing III.

To provide insights for understanding the differences in the average horizontal force coefficients presented above between various tandem wings, the time histories of C_H within one cycle for both forewings and hindwings are presented in Figure 4.2. It can be generally observed that all forewings and hindwings obtained two large peaks of horizontal force coefficients for every phase difference, one at about the middle of the upstroke and one at approximately the middle of the downstroke. The upstroke and downstroke periods in a cycle are illustrated

Figure 4.2: Time histories of horizontal force coefficients obtained by different wing models for both forewings and hindwings with phase differences of $\Psi=0^\circ$, 90° and 180° in the hovering flight. The white backgrounds represent the upstrokes, while the grey backgrounds represent the downstrokes. Star marks indicate the positions when the PIV analysis was performed for the tandem Wing III and rigid wings in Figure 4.3

with white and grey backgrounds, respectively, in Figure 4.2. Further, the upstroke peaks are higher than the downstroke peaks. In addition, the C_H values are mostly positive through the whole cycle, except during a short time when the wings reverse the plunging direction between the upstroke and downstroke.

Despite these common features, important differences do exist in the time histories of C_H between various cases studied, which account for the differences in the average horizontal force coefficients presented in Figure 4.1(a). If the rigid wings are excluded from consideration first, some consistent trends in C_H can be observed between the flexible wings. Firstly, the peak values of C_H in both up- and downstroke periods decrease when the wings are more flexible, except one special case on the hindwing at $\Psi=180^\circ$ during downstroke when the peak values between Wing II and Wing III are about the same. Secondly, there exist significant phase lags between different flexible wings in C_H during only the accelerating periods, or the first halves of both up- and downstrokes. The time traces of C_H are shifted more to the right with more flexible wings during acceleration. It is due to these important differences in peak values and phase lags during only the acceleration stage of the strokes that the average horizontal force coefficients, C_H , for less flexible tandem wings are higher than those for more flexible ones.

The differences in the time traces of C_H between tandem rigid and Wing III models, which caused the average C_H of Wing III much larger than that of rigid wings, are more complex. Nevertheless, a consistent feature that can be readily observed is the phase lag during the decelerating periods of the upstroke, or the second half of the upstroke, of both forewings and hindwings at each Ψ . The prolonged larger values of C_H during this quarter-cycle period is the most important reason why the average C_H for the tandem Wing III models are much higher than the rigid wings. Other features of the time histories of

C_H contribute to the average horizontal force coefficients in various ways. At $\Psi=0^\circ$, the peak values of C_H for Wing III are larger than the rigid wings, except during the downstroke for the forewing. In addition, before reaching the peak during the upstroke, the profiles of C_H for the rigid forewing and hindwings generated kinks with lower values as compared with the Wing III models. Further, a significant phase lag in the time traces of C_H developed during the whole quarter-cycle-long decelerating period of hindwings. All these factors add up to a dramatically higher average C_H for tandem Wing III models. However, when Ψ is equal to 90° , the four peak values of C_H for the rigid wings became higher and the phase lags in other periods, than the decelerating one during downstroke of the forewing, are much less obvious. As a result, the average C_H for Wing III at this Ψ of 90° is only about 6% higher than the rigid wings. For the case of $\Psi=180^\circ$, drastically higher peak values and the significant phase lag during the decelerating period of the hindwing's downstroke are the other main contributors for the tandem Wing III models to produce a high average horizontal force coefficient at this Ψ .

By comparing the vector and vorticity fields of tandem Wing III and rigid wings, the mechanisms of how wing flexibility caused the peak difference and phase lag in horizontal forces between the flexible and rigid wings are explained as follows. Figure 4.3 shows the average velocity vectors and vorticity contours for the tandem Wing III and rigid wings in 0° -phased situation at (i) $t/T = 0.228$, (ii) $t/T = 0.26$ and (iii) $t/T = 0.352$, where upstroke peaks of forewings, upstroke peaks of hindwings and phase lag between Wing III and rigid wings exists, respectively. At all these three time instances, tandem Wing III models obtained larger horizontal force than the tandem rigid wings.

Comparing the locations of Wing III and rigid wing models obtained from the 2D deformation measurements, significant spanwise bending deformation

Figure 4.3: Average velocity and vorticity fields for the tandem Wing III and rigid wings in 0° -phased situation at (i) $t/T = 0.228$, (ii) $t/T = 0.26$ and (iii) $t/T = 0.352$ in hovering flight. Red lines indicate the positions of wing models, while red dash lines in the results of Wing III models are the corresponding positions of rigid wings for comparison.

can be found at all three time instances. But there is almost no discernible torsional deformation, nor the change in camber. Due to the spanwise bending deformation, the tandem Wing III models always lagged behind the tandem rigid wings in plunging direction. Significant LEVs and TEVs can be observed on both forewing and hindwing at all three time instances. Stronger LEVs were produced on both the rigid forewing and hindwing at time instances (i) and (ii). At time instance iii, the tandem Wing III models produced LEVs with strength similar to those of tandem rigid wings. Because of the lags in plunging direction, the tandem Wing III models produced LEVs more attached to the wing models for both forewings and hindwings at all three time instances, which were of benefit to the horizontal force generation. The hind- Wing III model at time instances (i) and (ii) even had the LEVs attached on almost $1/3$ of wing model. At time instance (i), stronger TEV on the fore- Wing III contributed to a lower pressure region on the ventral surface, which also offered benefits to the horizontal force generation. Therefore, even with weaker LEV, the more attached LEV and stronger TEV both led to the higher upstroke peak of the fore- Wing III compared with the rigid forewing. Similarly, at time instance (ii), besides the more attached LEV, stronger TEV was also obtained by the hind- Wing III, which provided benefits to the higher upstroke peak of the hind- Wing III compared with the rigid hindwing. At time instances (iii), stronger TEVs were generated on both fore- and hind- Wing III models compared with the corresponding rigid wings. With more attached LEVs, and stronger TEVs, both fore- and hind- Wing III models obtained larger horizontal force than the corresponding rigid wings.

4.1.2 Forward flight at $f = 1Hz$ ($St = 0.6$)

The average horizontal force coefficients C_H , power coefficients C_P , and efficiency ε of tandem wings of various flexibilities at all three phase differences of 0° , 90° and 180° in the forward flight at oscillating frequency of $f = 1Hz$ are presented in Figure 4.4. Different from the hovering flight, the flexible tandem Wing III models achieve 14.4% higher C_H than the pair of rigid wings only at $\Psi=0^\circ$ in this forward flight. At other phase differences of 90° and 180° , the average horizontal force coefficients between Wing III and rigid tandem wings are almost similar. For the more flexible Wing II models, they obtain about the same C_H as the rigid wings at $\Psi=0^\circ$ while much lower values at the other phase differences. Again, the most flexible Wing I models produced dramatically lower horizontal force coefficients than the other tandem wings for all phase differences of Ψ .

It is also observed in Figure 4.4 (a) that the rigid wings generate the highest C_H at $\Psi=90^\circ$, which is consistent with other studies (Lan & Sun, 2001a; Rival *et al.*, 2011b). On the other hand, Wing II and III models obtain about the same C_H values at $\Psi=0^\circ$ and 90° , which are significantly higher than those at $\Psi=180^\circ$. At last, the difference in the average C_H between the studied phase differences for the most flexible Wing I models is trivial. Excluding the Wing I, the highest, albeit only marginally high, average horizontal force coefficient is produced by the tandem Wing III at $\Psi=0^\circ$, while the lowest value is generated by the tandem Wing II models at $\Psi=180^\circ$.

Similar to the hovering flight, the profiles of the average power coefficients, C_P , for this forward flight shown in Figure 4.4 (b) generally follow those of the average horizontal force coefficients, which again result in much smaller differences in the profiles of efficiencies illustrated in Figure 4.4 (c). However, different from the hovering flight, the efficiencies of Wing II and Wing III models

Figure 4.4: (a) Average horizontal force coefficient C_H , (b) power coefficient C_P , and (c) efficiency ε of tandem wings for different wing models in the forward flight at $f = 1Hz$.

are about the same at $\Psi=0^\circ$ and 90° , and are a little higher than those of the rigid wings at these two phase differences. But at $\Psi=180^\circ$, ε of Wing II is much lower than Wing III and rigid ones, while ε of Wing III is slightly higher than that of the tandem rigid wings.

In this forward flight, the single rigid hindwing achieved the highest average C_H when operated in isolation. Compared with it, the tandem Wing III models produced significantly higher average horizontal force coefficients, with 33.2% and 25% higher C_H values at $\Psi=0^\circ$ and 90° , respectively. In addition, both the tandem rigid wings and tandem Wing II models also generated higher C_H than that of the single rigid hindwing at 0° and 90° phase differences. However, at $\Psi=180^\circ$, the tandem Wing II, Wing III, and rigid wings produced about 30%, 7%, 6.3% lower average horizontal force coefficients, respectively, compared to the single rigid hindwing in isolation. For the efficiency, the tandem Wing III obtained almost the same ε as the single rigid hindwing at both $\Psi=0^\circ$ and 90° , while achieved about 9.4% lower ε at $\Psi=180^\circ$.

The time histories of the horizontal force coefficients for various tandem wings in the forward flight at oscillation frequency of 1 Hz are presented in Figure 4.5 to explain the production of the average C_H values shown in Figure 4.4. Generally, it can be observed that in addition to the differences in the peak values and phase lags between the time traces of C_H of various cases as in the hovering flight, there also exist significant secondary peaks in this forward flight which is another important factor to contribute to the average horizontal force coefficients, since the secondary peaks can keep the C_H at relative high values for a longer period of time.

At $\Psi=0^\circ$, obvious double peaks of C_H were developed during the transition from acceleration to deceleration during the upstroke motion of the forewings for all the three flexible wing models. But the rigid forewing lacks the secondary

Figure 4.5: Time histories of horizontal force coefficients obtained by different wing models for both forewings and hindwings at phase differences of 0° , 90° and 180° in the forward flight at $f = 1Hz$. Star marks indicate the positions when the PIV analysis was performed for the tandem Wing III and rigid wings in Figure 4.6.

peak. The peak values of C_H of the forewings during both up- and downstrokes decrease when the wings are more flexible. An obvious phase lag exists between the rigid and Wing III forewings during the decelerating period, or the second half, of the upstroke. However, the major phase lags between Wing II and Wing III forewings exist at the accelerating, or the first half, of both up- and downstrokes. The phase lags between the rigid and Wing II forewings appear during the whole cycle. Finally, the time histories of C_H for Wing I forewings are too low to compare with the other forewings for most of the cycle. For the hindwings, higher C_H values are produced by Wing III than the rigid hindwing during the two peak regions of up- and downstrokes, as well as during the deceleration period of the upstroke due to the major phase lag there. Comparing Wing III and Wing II hindwings, higher values of C_H are produced for Wing III hindwing due to the phase lags during the accelerating periods of both up- and downstrokes, as well as the much higher peak during the upstroke. Although the peaks of the rigid hindwing during both strokes are slightly lower than those of the Wing II hindwing, larger phase lags during the acceleration period of both strokes help the rigid hindwing compensate lower C_H values at other periods of the cycle.

At $\Psi=90^\circ$, horizontal forces produced by the hindwings are much larger than the forewings for all the wing models tested in this study. There is not much of the phase lag between Wing II and Wing III in the time histories of C_H of both forewings and hindwings. The major differences between these two flexible tandem wings lie in the peak regions. For the forewings, secondary peak values of C_H are only observed during the upstroke, but not in the downstroke. While the peak values are comparable, phase lags exist between the rigid and Wing III forewings, except during the acceleration of the upstroke. For the hindwings, obvious secondary peaks of C_H are found in all wing models, except

Wing III, during both strokes. Similar to the forewings, the major differences between Wing II and Wing III hindwings are in the peak regions rather than caused by the phase lags. Phase lags exist across the entire cycle between the rigid and Wing III hindwings. However, thanks to the prolonged higher values of C_H due to the secondary peak during the upstroke and the much higher peak value during the downstroke, the rigid hindwing produced significant horizontal forces to compensate the slightly less forces generated by the forewing, so that the average C_H of the tandem rigid wings at this Ψ is as large as that of the tandem Wing III.

At $\Psi=180^\circ$, although secondary peaks of C_H appear in every forewings during the upstroke, they are only developed by the rigid hindwings during the downstroke. Again, the time histories of C_H of the tandem Wing III are mainly different from those of the tandem Wing II during the peak regions. Similar to the case at $\Psi=90^\circ$, the main reason for the rigid tandem wings to produce the same average horizontal force coefficient as Wing III is due to the contribution from the hindwing through generating dramatically higher peak values of C_H .

Figure 4.6 shows the average velocity vectors and vorticity contours for the tandem Wing III and rigid wings in 0° -phased situation at (i) $t/T = 0.2$, (ii) $t/T = 0.368$ and (iii) $t/T = 0.7$, where the upstroke peaks of hindwings, phase lag between Wing III and rigid wings, and secondary peaks exists, respectively. At all these three positions, tandem Wing III models generated larger horizontal force than the tandem rigid wings. At position (i), not the entire LEV on the hind- Wing III model can be observed. However from the velocity vectors we can still tell that a large LEV may exist on the first 1/3 of the wing model. In forward flight, the Wing III models also lagged the rigid wings in plunging direction due to the bending deformation. This lag made the LEV more attached to the hind- Wing III compared with the rigid hindwing at position

Figure 4.6: Average velocity and vorticity fields for the tandem Wing III and rigid wings in 0° -phased situation at (i) $t/T = 0.2$, (i) $t/T = 0.368$ and (i) $t/T = 0.792$ in forward flight at $f = 1Hz$. Red lines indicate the positions of wing models, while red dash lines in the results of Wing III models are the corresponding positions of rigid wings for comparison.

i. Interestingly, the flow near the hind- Wing III models which is enclosed by the rectangle in Figure 4.6 showed much larger velocity than the corresponding flow near the rigid hindwing. This could be caused by the blockage effect of the lagged wings. This high velocity flow may induce low pressure which is also beneficial to the horizontal force generation. These two benefits brought by the bending deformation led to the higher upstroke peak of hind- Wing III than the rigid hindwing. In position ii, the LEV on the rigid hindwing is much stronger than that on Wing III model. However the LEV of hind- Wing III model existed on almost the whole wing model, which may be the reason accounting for the higher horizontal force of Wing III model. The LEV on the fore- Wing III was more attached to the wing model than that on rigid forewing, which resulted in the larger horizontal force. At position iii, we can also tell the large LEV from the velocity vectors on the hind- Wing III. What is more, the higher-velocity region can also be seen as marked in Figure 4.6. The higher-velocity region might be the main reason accounting for the higher horizontal force at this time instance.

4.1.3 Forward flight at $f = 0.5Hz$ ($St = 0.3$)

Figure 4.7 presents the average horizontal force coefficients, power coefficients and efficiencies of the tandem wings studied in the forward flight at a lower oscillation frequency of $f = 0.5Hz$. When the motion frequency is decreased from 1 Hz to 0.5 Hz, the horizontal force coefficients decreased accordingly. Additionally, the effects of phase difference and flexibility on the average C_H become more complicated.

It is only for the phase difference of $\Psi=0^\circ$ for this forward flight at $f=0.5Hz$ that the average horizontal force coefficient of tandem Wing I is comparable to those of Wing II and rigid wings. Average C_H values produced by Wing I

Figure 4.7: (a) Average horizontal force coefficient C_H , (b) power coefficient C_P , and (c) efficiency ε of tandem wings for different wing models in the forward flight at $f = 0.5Hz$

models decrease at larger phase differences and they are drastically smaller than the other wings at $\Psi=90^\circ$ and 180° . Still at $\Psi=0^\circ$, tandem Wing III generated about 80% more average C_H than the rest wings. At $\Psi=90^\circ$, all the wings except Wing I produced similar average forces, albeit the average C_H of the rigid ones is slightly larger than the other two. At $\Psi=180^\circ$, tandem Wing II and rigid wings have about the same average force coefficients while Wing III models get a slightly lower value. When comparing across the phase differences, Wing III obtained similarly high average C_H values in 0° and 90° phase differences, while Wing II and rigid wings produced the highest horizontal forces at $\Psi=90^\circ$.

Different from the other two flights, the trends of the power coefficients in this forward flight at $f=0.5$ Hz do not follow the force coefficients. At 0° phase difference, the power consumed by the tandem Wing III models is only slightly higher than the other wings, resulting in a much higher efficiency, as shown in Figure 4.7 (c). When $\Psi=90^\circ$, less power is associated with the tandem rigid wings, while there exist good correlations between the force generated and the power consumed for Wing II and Wing III ones. Therefore, the efficiencies of Wing II and III are similar, but that of the rigid wings is higher. At $\Psi=180^\circ$, less power is used to produce a higher force for the tandem Wing II, resulting in its highest efficiency at this phase difference.

Among all the single wings operated in isolation in this forward flight at $f=0.5$ Hz, the best performance was obtained by the hind- Wing III model, with the highest average C_H of 0.58 and highest ε of 0.29. Compared with it, the tandem wings, either rigid or flexible ones, did not show advantage. The best performer of tandem wings at $\Psi=0^\circ$, the Wing III, has the average C_H to be 5.4% lower than that of the single hind- Wing III at the same phase difference. At $\Psi=90^\circ$, average C_H of the tandem rigid wing, the best case at this phase difference, is only 5.9% higher than the single hind- Wing III.

The difference is much bigger at $\Psi=180^\circ$. The average C_H value of the largest force generator, the tandem rigid wings, is 23.4% lower than the single hind-Wing III at $\Psi=180^\circ$. Further, the efficiencies of all the tandem wings are also significantly lower than the single hind-Wing III. However, if the single rigid hindwing is used for comparison, some tandem wings can illustrate much better performances. For example, the tandem Wing III at 0° phase produced about 20% higher mean force coefficient, and the tandem rigid wings at $\Psi=90^\circ$ have an average C_H 33% higher than the single rigid Wing III operated in isolation.

Presented in Figure 4.8 are the time histories of the horizontal force coefficients for the tandem wings under the study for the forward flight at the oscillation frequency of 0.5 Hz. One common feature that can be observed in the figures is that a much larger portion of the cycle than the other two flights has negative force coefficients for all these tandem wings, which is the main reason to cause a lower average C_H for this forward flight at the lower oscillation frequency. Actually, a higher negative portion in the horizontal forces can also be observed in forward flight at $f = 1\text{Hz}$ when compared with the hovering flight. These increased negative forces in forward flights may be caused by the higher drag forces on the wing models induced by the incoming flow.

At $\Psi=0^\circ$, the major contribution to the average C_H for all tandem wings is observed to come from the forewing, rather than the hindwing as in other phase differences. Between the flexible forewings, the two peak values of C_H at the up- and downstrokes decrease consistently when the wings are more flexible. Although the forewing of Wing I still produces lower C_H across the majority of the cycle than the other flexible wings, the difference is now not as dramatic as the other two flights. While the phase lags during the decelerations of both strokes are quite small between the flexible forewings, they are progressively larger with more flexible wings during the accelerations of up- and

Figure 4.8: Time histories of horizontal force coefficients obtained by different wing models for both forewings and hindwings at phase differences of 0° , 90° and 180° in the forward flight at $f = 0.5Hz$

downstrokes. A comparison between the forewing of Wing III and the rigid one reveals several factors to cause such a lower average C_H for the rigid tandem wings: much lower peak values during the transition from acceleration to deceleration, deeper valleys during the transition from deceleration to acceleration, and the significant phase lags during decelerations of the cycle. For the hindwings, high frequency fluctuations exist in the time traces of C_H for all wing models, indicating a much more complex interaction between forewings and hindwings at this phase difference of 0° . This interaction seems to be more beneficial for the most flexible Wing I, since the time traces of C_H for the hind-Wing I are comparable to, and even much larger at some parts of the cycle than, the other wings.

At $\Psi=90^\circ$, secondary peaks appear in the time traces of C_H , but only for the hind-rigid and Wing III wings. The phase lags and the peak values between Wing III and Wing II are quite small. The major reason for the tandem Wing III to achieve slightly higher average C_H is due to the extra peak produced by the hindwing of Wing III. Although the values of C_H for the hindwing of Wing III during the upstroke peak region are obvious larger than the rigid hindwing and a relatively large phase lag exists during deceleration of the upstroke, the accumulated small phase lags eventually make the average C_H for the rigid tandem wings slightly higher than Wing III models. At last, at the phase difference of 180° , it is found that the time traces of C_H between Wing II, Wing III, and rigid wings are quite similar in peak values and phase lags, resulting in similar values of average C_H for these three tandem wings.

The comparison of average horizontal force coefficients and the efficiencies between the two forward flights at different oscillating frequencies is presented in Figure 4.9. It can be observed that the flight at $f=1$ Hz generated much larger average C_H in every case studied. The differences between the two forward

Figure 4.9: (a) Average horizontal force coefficient C_H and (b) efficiency ε of tandem wings for different wing models in forward flights at $f=0.5$ and 1 Hz.

flights are bigger in 0° and 90° phases. For the efficiency, the flight at $f=1$ Hz obtained larger ε generally. Only for the Wing III models at $\Psi=0^\circ$, the rigid wings at 90° , and the Wing II models at 180° , did the flight at $f=0.5$ Hz obtained slightly better efficiencies than the flight at $f=1$ Hz.

Different from what was found in previous studies for the real insects that the optimum Strouhal number for the efficiency is within 0.2 to 0.4 (Taylor *et al.*, 2003), we obtained the result that the flight at St of 0.6 ($f=1$ Hz) outperforms the flight at St of 0.3 ($f=0.5$ Hz) in most of the cases studied. However, this inconsistency of the Strouhal numbers is most likely to be caused by the difference between the real dragonfly wings and our wing models, and the difference between the real dragonfly's motion kinematics and the plunging/pitching motion employed in the present study as well. The real dragonfly wings show non-uniform distribution of bending stiffness due to veined and corrugated surface. Therefore, they have more complicated wing deformations than the wing models in the current study. Moreover, the current study simplified the motion of real dragonfly for easy motion realization, force and PIV measurements. This may also affect the effect of Strouhal number on the efficiency.

4.2 Summary and conclusions

In this chapter, the aerodynamic forces, power consumptions and efficiencies of tandem wings were measured in a hovering flight ($Re_{\overline{U}_P} = 4,544$) and forward flights at $f = 1Hz$ ($Re_{\overline{U}_P} = 4,544$ and $St = 0.6$) and $f = 0.5Hz$ ($Re_{\overline{U}_P} = 2,272$ and $St = 0.3$). Four tandem wing models were studied: rigid ones fabricated from the Aluminium sheet, and three flexible wing models made by rapid prototype printing. From less to more rigid, these three sets of flexible tandem wings were termed Wing I, Wing II and Wing III. Three phase differences of $\Psi=0^\circ$,

90°, and 180° between the forewings and hindwings were studied. Both the tandem configuration and wing flexibility showed great effects on the aerodynamic performance of tandem wings in all flights studied.

For the hovering flight, the tandem Wing III models outperform all the other wings with much larger horizontal force coefficients C_H and similar efficiencies ξ . 0° phase difference was found to be the most favorable phase difference for both rigid and flexible wing models.

For the forward flight at an oscillation frequency of 1 Hz ($St=0.6$), the Wing III models had advantages in aerodynamic performance over the rigid wings at the phase difference of $\Psi=0^\circ$ with larger horizontal force coefficient C_H and efficiency ε . At 90° and 180° phase differences, the Wing III models obtained C_H similar to the rigid wings, but ε was found larger than the rigid wings. Therefore, in general, the Wing III models still perform better than the other wing models. In this flight, both 0° and 90° phase differences were found to offer greater aerodynamic performance.

In the forward flights at a lower oscillation frequency of 0.5 Hz ($St=0.3$), the advantage of flexible tandem wings did not show in all situations studied. At 0° and 180°, the Wing III and Wing II models obtained the highest C_H and ε . However, at 90° phase difference, it was the rigid wings that performed best. Wing II, Wing III and rigid wing models all obtained their highest C_H at 90° phase difference, which suggests that 90° phase difference offered greatest benefits to this forward flight.

From the time histories of force coefficients of forewings and hindwings in both hovering and forward flights, it was observed that the phase lags between the force traces of flexible wing models and rigid wing models is another important reason, besides the different peak values, to cause the differences in the average horizontal force coefficients C_H . Moreover, secondary peaks of C_H

during the upstroke and downstroke periods were observed in the two forward flights studied. The secondary peaks can keep the C_H at high value for a longer period which is also greatly beneficial to the aerodynamic performance.

The results of PIV and deformation measurements explained how the flexibility contributed to the better aerodynamic performance of Wing III. The deformation of Wing III model is mainly the spanwise bending deformation. In hovering flight, the bending deformation led to a lag in plunging position of Wing III models which offered a more beneficial position to have the LEV more attached. In forward flight, in addition to the relative locations between the wings and the LEVs, the lagged wings blocked the incoming flow which resulted in a higher-velocity region. The higher-velocity region may induced low pressure field which may also contribute to the horizontal force.

Chapter 5

Time-resolved PIV study on the force dynamics of flexible tandem wings in hovering flight

The earlier studies have offered a lot of information on how the tandem-wing configuration and flexibility affect the aerodynamic performance with flow fields through the cycle or at specified time instances. However, few of them associated the flow fields with the dynamics of aerodynamic forces, which is one of the important aspects of the aerodynamic performance. In chapter 4, the aerodynamic performance of the flexible tandem wings has been investigated. It has been shown that both the phase difference and flexibility had significant effect on the aerodynamic performance of flexible tandem wings. What is more, it was shown that there were significant differences in force dynamics between the flexible and rigid wings when comparing the force traces. In this chapter, to offer more insights into the aerodynamic performance of flexible tandem wings in hovering flight ($Re_{\overline{U}_p} = 4,544$), 3D deformation and time-resolved PIV measurements were carried out. The dynamics of aerodynamic forces will be analyzed in detail. According to the flow fields obtained from the time-resolved PIV measurements, the mechanisms how the flexibility and phase difference affect the force dynamics will be explained.

5.1 Results and discussions

In chapter 4, the lift generation of flexible tandem wings (Wing I, Wing II and Wing III) and rigid tandem wings were studied in hovering flight at phase

Table 5.1: Average lift coefficients of different wing models in single-wing and tandem-wing configurations

Wing Model	Single		Tandem								
			0°			90°			180°		
	Fore	Hind	Fore	Hind	Total	Fore	Hind	Total	Fore	Hind	Total
I	0.711	1.176	0.660	1.081	0.897	0.754	1.098	0.948	0.637	1.105	0.901
II	1.483	1.785	1.757	1.987	1.887	1.438	1.581	1.519	1.374	1.466	1.426
III	1.781	1.944	2.086	2.238	2.172	1.705	1.820	1.769	1.646	1.550	1.592
Rigid	1.467	1.639	1.847	1.844	1.845	1.497	1.805	1.671	1.414	1.270	1.333

differences of 0°, 90° and 180°. The results showed that both the phase difference and flexibility had significant effect on the lift generation. Table 5.1 provides the average lift coefficients of the forewings and hindwings in both single-wing and tandem-wing configurations. With appropriate flexibility, the tandem Wing III models outperformed the other wing models in all cases studied. Comparing the force traces of flexible and rigid wings in chapter 4, it was found that: 1) Except for the Wing I model which obtained dramatically low lift due to the excessive flexibility, the flexible wing models obtained similar force dynamics generally in either single-wing or tandem-wing configuration; 2) Significant differences in force dynamics between the flexible and rigid wings were found. Since the Wing III model was shown to outperform the other flexible wing models and to have the force dynamics similar to that of Wing II, our analysis will mainly focus on the Wing III model, with the rigid wings as the reference.

5.1.1 Benchmark case: single-wing configuration

Before investigating the force dynamics of tandem wings, it is necessary to study the single-wing configuration first. The force dynamics and the relevant mechanisms of single-wing case were investigated to offer benchmark for the tandem-wing cases. By comparing the force traces of single-wing and tandem-

wing cases, how the phase differences change the force dynamics can be revealed. Furthermore, the flow fields of single-wing cases were also provided as the reference to investigate how the forewing-hindwing interactions affect the flow fields of tandem-wing cases.

Figure 5.1 shows the time histories of lift coefficients obtained by the Wing III and rigid wing models for the forewings and hindwings. It can be observed that the effect of flexibility on the force traces was remarkable. Generally, there were significant lags between the force traces of rigid wings and Wing III models during the deceleration periods of both up- and down-strokes ($t/T = 0.25 \sim 0.5$ and $t/T = 0.75 \sim 1$). A much larger upstroke peak was obtained by the fore-Wing III compared with the rigid forewing, while similar values were acquired by the Wing III and rigid wing models for the downstroke peak of forewing and up- and downstroke peaks of hindwing. The lags between the force traces of wing models mainly account for the differences in the mean lift coefficients. What's also important, the Wing III models produced quite different dynamics on the force traces than the rigid wings. For the hindwings, during $t/T = 0.136$ to 0.24 on the upstroke, the lift of the Wing III increased smoothly, while the rigid wing obtained a significant kink. At first, the lift of the rigid hindwing slowed down the trend of increase, then almost maintained at a constant value during $t/T = 0.16$ to 0.2 , afterwards the lift continued to increase again, but with much lower value than the hind- Wing III. During the time from $t/T = 0.64$ to 0.72 on the downstroke, there was also a small kink on the force trace of rigid hindwing. In contrast, during the same time interval, the hind- Wing III obtained small peaks, i.e. the secondary peaks, instead of the kink. The kinks were also found on the rigid forewing during $t/T = 0.108$ to 0.18 on the upstroke, and $t/T = 0.64$ to 0.72 on the downstroke. The secondary peak on the hind- Wing III was not observed on the fore- Wing III. A kink was

Figure 5.1: Time histories of lift coefficients obtained by different hind- wing models in single-wing configuration. The white background represents the up-stroke, while the grey background represents the downstroke.

generated during $t/T = 0.64$ to 0.72 instead. Since the single forewings and hindwings obtained similar force dynamics, the hindwings were chosen to be further studied to uncover the mechanisms of the kinks and the secondary peak by investigating the deformation of the hind- Wing III model, as well as the flow fields of the hind- Wing III and rigid wing during $t/T = 0.136$ to 0.24 and $t/T = 0.64$ to 0.72 . The results are shown as follows.

Figure 5.2 shows the deformations of hind- Wing III during the motion compared with the rigid hindwing. Significant spanwise bending deformation can be observed on the Wing III model. Due to the bending deformation, the Wing III model lagged the rigid wing in plunging direction. And this lag became larger when the wings approached the mid-stroke location where the wings achieved the maximum plunging velocity. Moreover, the further the location was away from the wing root, the larger the lag was. However, as shown in Figures 5.4 and 5.5, no discernible difference in angle of attack or camber was found when comparing the cross sections of Wing III and rigid wing at 25%, 50% and 75% spanwise location. The change in angle of attack was also calculated with the reconstructed three dimensional locations of wings. The

Figure 5.2: The deformations of hind- Wing III (red) with rigid wing (blue) as reference in single-wing configuration at different time instances ($t^* = t/T$) during upstroke and downstroke.

deformation of Wing III model resulted in about 0.5° larger angle of attack than the rigid wing at the mid-stroke location where the largest deformation was obtained. Therefore, the effect of the difference in angle of attack was regarded negligible.

The flow fields of Wing III and rigid wing at 25%, 50% and 75% spanwise locations obtained from TR-PIV measurements were compared to study the effect of bending deformation on the lift dynamics. Before analyzing the TR-PIV results, 3D flow models of the rigid hindwing are constructed in Figure 5.3 to offer a better understanding of the flow fields. The vortex loop on the rigid hindwing consists of leading edge vortex (LEV), training edge vortex (TEV), tip vortex (TV) and root vortex (RV). The reconstructions of LEVs and TEVs are based on the TR-PIV results at 25%, 50% and 75% spanwise locations. However, due to the lack of data at wing tip and root, the reconstructions of the TVs and RVs are based on the flow visualization work by Lua *et al.* (2010). Therefore, the present study will focus on the discussions on the LEVs and TEVs. Besides, the flow developments during upstroke and downstroke are

similar due to the symmetrical motion. Therefore, only the flow development during upstroke is analyzed herein. As shown in Figure 5.3, at the start of upstroke, i.e. time instance (i), LEV_D and TEV_D indicate the vortices shed in the previous downstroke. At the same time, the flow around the leading edge begins to roll up to form a new LEV (see LEV_{U1} in Figure 5.3 (i)). As the wing accelerates, the flow around the wing also rolls up at trailing edge, wing tip and wing root, thus forming a vortex loop with the approximate shape of the wing planform (see Figure 5.3 (ii)). The ' TEV_D ' has dissipated at this time instance, while the ' LEV_D ' becomes weak and diffused. When the wing moves to time instance (iii), the portion of the vortex loop at the leading edge, i.e. LEV_{U1} , begins to show trend of shedding with new leading edge vortex, LEV_{U2} , generated. The same situation happens at the training edge at time instance (iv). The LEV_{U1} and TEV_{U1} shed at time instances (iv) and (v), respectively. During period from (iii) to (v), LEV_{U2} and TEV_{U2} keep growing, instead of showing trend of shedding like LEV_{U1} and TEV_{U1} . This is because that the wing begins to decelerate from time instance (v), which restrains the shedding. As the wing enter the 'finishing stage' of the upstroke, i.e. (vi) and (vii), the LEV_{U2} and TEV_{U2} has gained sufficient strength (see Figure 5.3 (vi)) and finally shed (see Figure 5.3 (vii)). Comparing Figure 5.3 (vii) and (i), it can be observed that the LEV_{U2} and TEV_{U2} act in the way similar as the LEV_D and TEV_D , which indicates that the flow developments in the upstroke and downstroke are similar.

Comparing Figure 5.1 and Figure 5.3, the lift coefficient trace can be associated with the flow development for the rigid hindwing. At the beginning stage of the upstroke, the LEV_{U1} and TEV_{U1} keep growing (see Figure 5.3 (i) and (ii)). Besides, the angle of attack is also increasing. These two factors lead to the increasing lift coefficient during $t/T = 0$ to 0.136. As the LEV_{U1} and

TEV_{U1} begin to shed (see Figure 5.3 (iii)), a kink was generated on the lift coefficient trace during $t/T = 0.136$ to 0.2 . The lift coefficient reaches peak near $t/T = 0.25$ with maximum angle of attack and strong LEV_{U2} and TEV_{U2} . During the second half of upstroke, the lift coefficient keeps decreasing due to the decreasing angle of attack. Since the LEV_{U2} and TEV_{U2} don't shed as the LEV_{U1} and TEV_{U1} , no kink on the lift coefficient trace was observed in the second half of upstroke.

Figures 5.4(i) to (vi) show the TR-PIV results for the hind- Wing III and rigid wing during the period $t/T = 0.136$ to $t/T = 0.24$, when the rigid hindwing obtained a kink while the hind- Wing III did not. During $t/T=0.136$ to 0.2 , the LEVs on rigid wing at 25% and 50% spanwise locations showed obvious trend of shedding. In the present study, the shedding of vortex is similar to continuous Von Karman shedding behavior. The shedding of LEV should result in reduction in lift generation. But the resultant force acting on the wing model became larger during this period due to the increasing plunging velocity. Moreover, the angle of attack also kept increasing, which offered benefits in decomposing of force in lift direction. These contradictory effects finally resulted in the constant lift generation during $t/T=0.136$ to 0.2 . As the LEV was shed, a new LEV was also generated and developed. Till $t/T = 0.216$, the old LEV was almost shed, while the new LEV was developed to be a strong LEV on the rigid wing. Therefore, the lift generation continued to increase afterwards. Throughout the entire process, the LEV at 75% spanwise location of rigid wing always kept attached and grew slowly.

Comparing with the rigid wing, due to the effect of lag in plunging direction, the Wing III model produced remarkably stronger LEV during $t/T = 0.136$ to 0.24 at all three spanwise locations. Both the Wing III and rigid wing generated strong TEVs within this period. But after $t/T = 0.2$, the Wing III

Figure 5.3: Sketches (i) to (vii) show the authors' interpretation of the flow development during upstroke for the single rigid hindwing in both 3D perspective view (side view) and 2D sectional view (top view). The results in 2D sectional view are for the flow fields at 50% spanwise locations. (a) and (b) presents the locations of the wing models at time instances (i) to (vii) from side view, and the corresponding locations of wing models at 50% spanwise location from top view, respectively. The black solid dots on the wing models indicate the leading edges. The plunging and pitching directions are marked with dashed arrows. Note that the leading edges of wing models in this figure are on the right side for more intuitive description, which are different from those in the other figures.

Figure 5.3 continued

(i) $t/T=0.136$

Figure 5.4. (i)

(ii) $t/T=0.16$

Figure 5.4. (ii)

(iii) $t/T=0.176$

Figure 5.4. (iii)

(iv) $t/T=0.2$

Figure 5.4. (iv)

Figure 5.4. (v)

model obtained slightly stronger TEVs at 25% and 50% spanwise locations. The stronger LEVs and TEVs induced a lower pressure region to increase the pressure difference between the dorsal and ventral surfaces, which should mainly account for the much larger lift generation of Wing III than the rigid wing. The other important effect brought by the lag was that the shedding of LEV was relatively restrained especially at the 25% location. This may explain the continually increase of lift generation on the Wing III model $t/T = 0.136$ to 0.2, instead of a kink as on the rigid wing. Moreover, this 'restrained shedding' effect also contributed to the stronger LEV on the Wing III model by keeping the LEV growing instead of shedding. The LEV at 75% spanwise location of Wing III was also attached through $t/T = 0.136$ to 0.24.

Figure 5.5(i) to (v) present the flow fields of Wing III and rigid wing at 25%, 50% and 75% spanwise locations through $t/T = 0.64$ to 0.72. Similar to the flow fields during $t/T = 0.136$ to 0.24, the shedding of LEV on the rigid wing was also

Figure 5.4: (i)-(vi) Average velocity and vorticity fields for the single hind-Wing III model and rigid wing at 25%, 50% and 75% spanwise locations during $t/T = 0.136$ to 0.24 . Red solid lines indicate the positions of wing models, while red dash lines in the results of Wing III models are the corresponding positions of rigid wings for comparison. In the results of rigid wing, the regions with black border are offered by the other set of data with the laser illuminating from the opposite side. The plunging and pitching directions are marked on the rigid wing at 25% spanwise location.

(i) $t/T=0.64$

Figure 5.5. (i)

(ii) $t/T=0.656$

Figure 5.5. (ii)

(iii) $t/T=0.68$

Figure 5.5. (iii)

(iv) $t/T=0.696$

Figure 5.5. (iv)

Figure 5.5: (i)-(v) Average velocity and vorticity fields for the single hind- Wing III model and rigid wing during $t/T = 0.64$ to 0.72 .

observed during this period. Therefore, the rigid wing obtained another kink on the lift trace. The lag caused by the bending deformation also led to the stronger LEVs on the Wing III model at 25% and 50% spanwise locations. Moreover, the TEVs on the Wing III at 25% and 50% spanwise locations obtained slightly larger strength than the rigid wing during $t/T = 0.696$ to 0.72 . As for the 75% spanwise location, the LEVs on Wing III and rigid wing both kept attached through this period, with the LEV of Wing III obtaining higher strength. These factors all contributed to the higher lift of Wing III than the rigid wing. As explained for period $t/T = 0.136$ to 0.24 , the stronger LEV on the Wing III model is the result of 'restrained shedding' effect. The lift coefficients of Wing III kept increasing from $t/T = 0.64$ to 0.67 , but then decreased till $t/T = 0.72$. Even though the shedding of LEV was relatively restrained on the Wing III compared with the rigid wing, significant shedding trend was still observed at

25% and 50% spanwise locations from $t/T = 0.68$ to 0.72 . As explained for the kink on the rigid wing during the upstroke, the decreasing effect brought by the shedding of LEV and increasing effect brought by the change in plunging velocity and angle of attack both acted on the wing model. During $t/T = 0.68$ to 0.72 , the effect of shedding LEV may be more dominant than the effect of plunging velocity and angle of attack, which led to the reduction in the lift generation. Afterwards, a new strong LEV was developed which increased the lift again to generate the second peak on the downstroke.

For the forewings of both Wing III and rigid wing models, the flow fields similar to those of the corresponding hindwings were observed during $t/T = 0.108$ to 0.18 and $t/T = 0.64$ to 0.72 . The contradictory effects of the shedding LEVs and the increasing plunging velocity and angle of attack, also resulted in the kinks on the force trace of rigid forewing during the up- and downstrokes, and the kink on the force trace of fore- Wing III during the downstroke.

5.1.2 Tandem-wing configuration at $\Psi = 0^\circ$

Figure 5.6 shows the time histories of lift coefficients obtained by the forewings and hindwings in tandem-wing configuration with phase difference of $\Psi = 0^\circ$. The results of single forewing and hindwing are also presented as the reference to investigate how the tandem effect changes the lift generations. At $\Psi = 0^\circ$, the lags between the force traces of Wing III and rigid wings during the deceleration periods also existed. The tandem effect generally increased the lift coefficient of forewing for both Wing III and rigid wing. The lift dynamics of forewings was not changed significantly when compared with the corresponding single-wing cases. For the rigid forewing, the kinks on the force trace of single-wing case were also observed in this tandem-wing case at the same time interval. But the kink on the fore- Wing III in single-wing case during $t/T = 0.64$ to 0.72

Figure 5.6: Time histories of lift coefficients obtained by forewings and hindwings in tandem-wing configuration with phase difference of $\Psi=0^\circ$. The solid lines are the tandem-wing cases, while the dashed lines are the single-wing cases for reference. The differences between the tandem-wing cases and single-wing cases were marked as red-coloured and shaded areas for the Wing III and rigid wing models, respectively. The white and grey backgrounds represent the up- and downstrokes of forewings.

was smoothed-out in this tandem-wing case. The lift generations of hindwings were also generally increased. What is more important, during $t/T = 0.64$ to 0.72 , the kink of single rigid wing and the secondary peak of single Wing III were both eliminated by the tandem effect at this phase difference. The differences between the tandem-wing and single-wing cases during this period were marked as red-coloured and shaded areas for the Wing III and rigid wing models, respectively.

The bending deformation can be observed on both fore- and hind- Wing III models in 0° -phased case, as shown in Figure 5.7. Similar to the single-wing case, the lags between the Wing III and rigid wing models in plunging direction became larger when the location became further away from the wing root. The wing models at 25%, 50% and 75% spanwise locations were also indicated in the flow fields during $t/T = 0.64$ to 0.72 (see Figure 5.8). Interestingly, the bending deformations showed different effects on the relative positions of forewing and hindwing at three spanwise locations during this period. The fore- Wing III

model got little bending deformation at 25% spanwise location so that it almost overlapped the rigid forewing as shown in Figure 5.8. But the fore- Wing III showed larger bending deformation than the hind- Wing III at 75% spanwise location due to its longer span length. At 50% spanwise location, the fore- and hind- Wing III obtained similar bending deformations. The different bending deformations of fore- and hind- Wing III models changed the gap between the tandem Wing III models. Therefore, compared with the gaps between the tandem rigid wings, the tandem Wing III models obtained smaller, comparable and larger wing gaps at 25%, 50% and 75% spanwise locations, respectively. The modified wing gaps resulted in different effects on the interactions of tandem Wing III when compared with the tandem rigid wings.

The comparisons between the force traces of the tandem-wing and single-wing cases show that the tandem effects mainly change the force dynamics during $t/T = 0.64$ to 0.72 . Figure 5.8 presents the average velocity and vorticity fields for the tandem Wing III and rigid wings during $t/T = 0.64$ to 0.72 . The tandem-wing configuration at 0° phase difference was found to show more significant effect on the hindwings than on the forewings. Therefore, the following analysis of the flow fields will concentrate more on the hindwings.

With both wing lags and changes in relative positions of tandem wings, the flexibility of wing models were found to change the flow fields in tandem-wing configuration in more ways than in single-wing configuration. At 50% spanwise location, the tandem Wing III and rigid wings obtained almost same wings' gaps. But both the forewing and hindwing of the tandem Wing III models lagged the tandem rigid wings in plunging direction due to the bending deformation. Compared with the tandem rigid wings, these lags led to LEVs closer to the wing surface on the hind- Wing III model through $t/T = 0.64$ to 0.72 , which was beneficial to the lift generation of hind- Wing III model. The

Figure 5.7: The deformations of Wing III models (red) with rigid wings (blue) as reference in 0° -phased tandem-wing configuration at different time instances ($t^* = t/T$) during upstroke and downstroke.

Figure 5.8. (i)

(ii) $t/T=0.68$

Figure 5.8. (ii)

(iii) $t/T=0.72$

Figure 5.8: (i)-(iii) Average velocity and vorticity fields for the tandem Wing III models and rigid wings at $\Psi=0^\circ$ during $t/T = 0.64$ to 0.72 .

lags were small at 25% spanwise location. However, with a narrower gap, the flow induced by the fore- Wing III was more towards the hindwing compared with that of rigid forewing. This flow then induced the LEVs on the hind- Wing III to be closer to the wing model, which also benefited the lift generation of hind- Wing III models. Different from the 25% spanwise location, the gap was smaller for the tandem rigid wings than the tandem Wing III models at 75% spanwise location. Therefore, the rigid hindwing obtained a more attached LEV than the hind- Wing III model with the rigid forewing offering more beneficial induced flow.

Besides the locations of LEVs, the strength of the LEVs also varied. At $t/T = 0.64, 0.68$ and 0.72 , the rigid hindwing all obtained remarkable stronger LEVs than the flexible wings at 25% spanwise locations. At 50% location, the LEVs of Wing III were slightly stronger at $t/T = 0.64$ and 0.68 , while weaker at $t/T = 0.72$ than the rigid hindwing. Stronger LEVs were obtained by the hind- Wing III at 75% spanwise location at all these three time instances. Generally, weaker but closer LEVs were obtained by the hind- Wing III at 25% and 50% spanwise locations, which also happened to the rigid hindwing at 75% location. Finally, the various situations in strength and location of LEVs resulted in the comparable lift generations of hind- Wing III and rigid wing at these three time instances.

By comparing the flow fields of hindwings in tandem-wing (Figure 5.8) and single-wing (Figure 5.5) situations, the mechanism of how the tandem-wing configuration changed the force dynamics of hind- Wing III and rigid wing during $t/T = 0.64$ to 0.72 were investigated. For the rigid wings, the LEV on the hindwing showed obvious trend of shedding in single-wing configuration which stopped the increase of lift and generated a kink on the lift trace. In 0° -phased tandem-wing configuration, the existence of TEV on the forewing

induced stronger and closer LEVs on the hindwing at all three spanwise locations when compared with the corresponding single-wing case. The TEVs were also changed in strength and location. At $t/T = 0.64$, the TEVs at 25% and 50% spanwise locations were both weakened while the TEV at 75% spanwise location was enhanced when compared with the corresponding single-wing case. At this time instance, the weakening of TEV on tandem hindwing at 25% spanwise location was caused by interaction between the TEV and shed LEV of hindwing from previous stroke (see 25% spanwise locations in Figure 5.8(i) and Figure 5.5(i)). On the contrary, the enhancement of TEV on tandem hindwing at 75% spanwise location was caused by interaction between the TEV and shed TEV of forewing from previous stroke (see 75% spanwise locations in Figure 5.8(i) and Figure 5.5(i)). When the wings continued to move to $t/T = 0.68$ and $t/T = 0.72$, only the TEVs at 25% spanwise location were found to be weakened while the TEVs at the other locations were enhanced. The interactions between the TEVs and the shed forewing's TEV as well as hindwing's LEV from previous stroke were also observed. The enhanced and closer LEVs, and the enhanced TEVs, all greatly contributed to the lift generation of the hindwing of tandem rigid wings. What is more, the flow induced by the forewings also slightly restrained the shedding of the LEVs through $t/T = 0.64$ to 0.72 , which also offered benefits to the lift generation. Finally, all these effects led to the elimination of kink on the lift trace of the rigid hindwing in tandem-wing configuration at $\Psi = 0^\circ$. Furthermore, the lift was increased significantly compared with the single-wing case and kept increasing from $t/T = 0.64$ to 0.72 .

For the tandem Wing III models, the LEVs at 25% location at all three time instances were weakened in tandem-wing case compared with the corresponding single-wing case. The strengths of LEVs at 50% locations were not changed much in tandem-wing configuration, while the LEVs at 75% locations were

enhanced significantly. Similar to the tandem rigid wings, all the LEVs were induced to be closer to the hind- Wing III model by the TEVs on the forewings, which contributed to the lift generation. However, due to the existence of forewing, strong TEVs as in the single-wing configuration no longer existed on the hind- Wing III model in 0° -phased tandem-wing configuration. Weak or diffused TEVs were generated on the hindwing of tandem Wing III. Therefore, even with closer LEVs, the forewing still caused reduction in lift generation of hindwing from $t/T = 0.64$ to 0.68 . In single-wing case, the lift started to decrease after $t/T = 0.68$ due to the shedding of LEV. In 0° -phased tandem-wing case, the existence of forewing significantly restrained the shedding of LEVs on the hind- Wing III through $t/T = 0.64$ to 0.72 . So the hind- Wing III got continuously increasing lift after $t/T = 0.68$.

The forewing-hindwing interaction also affected the unsteady aerodynamics of the forewings. With 0° phase difference, the forewing and hindwing were very close during motions, which led to the significant blockage effect of the hindwing on the forewing. Comparing the velocity fields of single-wing and tandem-wing cases, the blockage effect greatly enhanced the induced flow of forewings near the training edge, which resulted in the slightly stronger TEV on the forewing in 0° -phased case. With this enhancement, additional positive lift was generated so that the small kink on the force trace of fore- Wing III during the downstroke was also smoothed-out. The tandem-wing configuration showed little effect on the locations of LEVs and TEVs on the forewings when compared with the corresponding single forewings. Therefore the flow fields of single forewings are not presented here for detailed comparisons.

To offer a better understanding of the interaction between the forewing and hindwing, the schematic reconstructions of vortices and flow pattern for the 0° -phased Wing III and rigid wings at 25% spanwise locations at $t/T = 0.64$

are presented in figure 5.9. It was observed that the tandem Wing III model obtained a LEV on the hindwing much closer to the wing model than that of tandem rigid wing. This could be partially attributed to the lag in plunging motion, which also led to the closer LEV on the Wing III models in single hindwing cases (see Figure 5.9). What is more important, the modification in relative positions of tandem wings, i.e. smaller wing gap between tandem Wing III, led to different flows between the fore- and hindwing. As indicated by the blue arrows in Figure 5.9, the direction of the flow between tandem Wing III was more towards the hindwing than that between tandem rigid wings, which accounted much for the closer LEV on hind- Wing III. When comparing the tandem wings with the corresponding single cases, the forewings both showed favourable effects by contributing to the LEVs closer to the hindwings. Here the flow patterns for the single-wing cases were not presented since there was no relatively uniform flows as that between the tandem forewing and hindwing (see Figure 5.6(i)). For 90° - and 180° -phased cases, the basic mechanism of forewing-hindwing interactions are similar to those of 0° -phased cases, i.e. modifications in the LEV on the hindwing and the flow between tandem wings. Therefore, the physical models of the forewing-hindwing interactions at $\Psi = 90^\circ$ and 180° will not be further discussed.

5.1.3 Tandem-wing configuration at $\Psi = 90^\circ$

As shown in Figure 5.10, the time histories of lift coefficients for the tandem Wing III and rigid wings at $\Psi = 90^\circ$ are presented with the corresponding single-wing cases as the reference. The time axes for the results of forewings and hindwings both start at the beginning of forewings' plunging motion. The lags between the force traces of Wing III and rigid wing models can be also observed in this tandem-wing case. At this phase difference, the up- and down-

Figure 5.9: Schematic reconstruction of vortices and flow between fore- and hindwings for 0° -phased tandem Wing III and rigid wings at 25% spanwise location at $t/T = 0.64$. The single-hindwing cases are also presented as references. The solid lines indicate the positions of wing models, while dash lines in the results of Wing III models are the corresponding positions of rigid wings for comparison. The flows between fore- and hindwings are relatively uniform for both tandem Wing III and rigid wings. So the blue arrows are used to estimate their directions. The plunging and pitching directions are marked on the tandem rigid wings case with dashed arrows.

stroke peaks were both enhanced by the tandem effects for the rigid forewing, while both weakened for the fore- Wing III. The tandem-wing configuration also affected the force dynamics of forewings. During the downstroke of forewings, the little kinks on the single Wing III and rigid wing were both smoothed-out in the 90° -phased tandem-wing configuration. For the hindwings, the tandem effects also resulted in higher up- and downstroke peaks of rigid wing and lower up- and downstroke peaks of Wing III, when compared with the corresponding single-wing cases. The rigid hindwing obtained remarkably higher peaks than the hind- Wing III. What's interesting, the tandem-wing configuration resulted in quite different force dynamics for the hind- Wing III and rigid wing during $t/T = 0.34$ to 0.6 . From $t/T = 0.34$ to 0.44 , the lift coefficients of both Wing III and rigid wing were reduced by the tandem effect compared with the corresponding single-wing cases. Moreover, the kink on the single rigid hindwing was smoothed-out in this tandem-wing case. The secondary peak on the Wing III model no longer existed either, and was replaced by a kink. After $t/T = 0.44$, the lift of rigid hindwing increased dramatically to reach a much higher peak than the single-wing case. Different from the rigid hindwing, the lift of hind- Wing III increased slowly, and obtained a peak with lower value than that of single-wing case. When the wing models moved to $t/T = 0.6$, the rigid hindwing obtained a small kink while the hind- Wing III did not. As shown in Figure 5.10, the differences between the tandem and single-wing cases during $t/T = 0.4$ to 0.52 were marked. During this period, however, the tandem-wing configuration showed little effect on either the fore- Wing III or the rigid forewing in both the force dynamics and value. Therefore, the flow fields of tandem wings during $t/T = 0.4$ to 0.52 will be analyzed with the focus on the hindwings.

In 90° -phased tandem-wing configuration, the lags between the Wing III

Figure 5.10: Time histories of lift coefficients obtained by forewings and hindwings in tandem-wing configuration with phase difference of $\Psi=90^\circ$. The solid lines are the tandem-wing cases, while the dashed lines are the single-wing cases for reference. The differences between the tandem-wing cases and single-wing cases were marked as red-coloured and shaded areas for the Wing III and rigid wing models, respectively. The white and grey backgrounds represent the up- and downstrokes of forewings.

and rigid wing models due to the bending deformations were also found. Different from the 0° -phased tandem-wing cases, the lags caused quite different relative positions of forewings and hindwings for the tandem Wing III and rigid wings, when the forewings and hindwings were plunging close to each other. As shown in Figure 5.11, the deformations of tandem Wing III models with the tandem rigid wings as reference at $t/T = 0.4$ are presented. At this time instance, the forewings and hindwings were plunging in opposite directions. Due to the bending deformations, both the fore- and hind- Wing III lagged their corresponding rigid wings. The relative position of fore- and hind- Wing III models in plunging direction were therefore changed. What is more important, as the spanwise location became further away from the wing root, the relative position between the fore- and hind- Wing III models were completely changed compared with that of tandem rigid wings.

In Figure 5.12, the locations of tandem Wing III and rigid wings during $t/T = 0.4$ to 0.52 were compared at 25%, 50% and 75% spanwise locations, re-

spectively. At 50% spanwise location, the rigid forewing and hindwing just encountered and plunging away from each other at $t/T = 0.4$ (see Figure 5.12(i)). However, with the lags, the fore- and hind- Wing III models were still far away from each other. This difference became more significant as the location was further away from the wing root, especially at 75% spanwise location. At 25% spanwise location, there was almost no lag between the fore- Wing III and rigid wing, while only a little lag between the hind- Wing III and rigid wing. So the relative position of tandem Wing III at 25% spanwise location was not changed much. Similarly, at the later time instances $t/T = 0.44, 0.48$ and 0.52 (see Figures 5.12(ii) to (iv)), the differences between the relative positions of forewings and hindwings for Wing III and rigid wings at 25% were all very small. During $t/T = 0.44$ to 0.52 , the forewing and hindwing of Wing III model had also encountered each other and were moving away from each other. As seen in Figures 5.12(ii) to (iv), the gaps between tandem Wing III models became smaller than that of tandem rigid wings at 50% and 75% spanwise locations. When the wing models moved to time instance $t/T = 0.48$ and 0.52 , the forewings' plunging velocity was close to zero. Therefore, the lags between the fore- Wing III and rigid wing at all three spanwise locations were quite small.

With the different relative positions, the interactions between the forewings and hindwings were changed accordingly. By analyzing the flow fields for the tandem Wing III and rigid wings during $t/T = 0.4$ to 0.52 , the force dynamics of hind- Wing III and rigid wings can be explained. At 25% spanwise location, the TEV of fore- Wing III shed at $t/T = 0.4$. The remaining TEV on the fore- Wing III and LEV on the hind- Wing III were both too small to merge with each other at $t/T = 0.44$. Till $t/T = 0.48$ the hind- Wing III merged with the shed TEV of forewing at $t/T = 0.52$ to enhance the LEV on the hind- Wing III. Different from the Wing III models, the TEV on the rigid forewing

Figure 5.11: The deformation of Wing III models (red) with rigid wings (blue) as reference at $t^* = t/T = 0.4$ in 90° -phased tandem-wing configuration and at $t^* = t/T = 0.296$ in 180° -phased tandem-wing configuration.

Figure 5.12. (i)

(ii) $t/T=0.44$

Figure 5.12. (ii)

(iii) $t/T=0.48$

Figure 5.12. (iii)

Figure 5.12: (i)-(iv) Average velocity and vorticity fields for the tandem Wing III models and rigid wings at $\Psi=90^\circ$ during $t/T = 0.4$ to 0.52 .

at 25% spanwise location was not shed at $t/T = 0.4$. With larger LEV on the hindwing and slightly smaller gap between wings, the rigid hindwing caught the TEV on the forewing early at $t/T = 0.44$. It further caught the shed TEV at $t/T = 0.48$ and combined all of them to become a strong LEV on the hindwing at $t/T = 0.52$. This contributed to the faster growth of lift generation of rigid hindwing than the hind- Wing III through $t/T = 0.44$ to 0.52 .

At 50% spanwise location, the rigid forewing and hindwing encountered each other at $t/T = 0.4$, i.e. the 1/4-chord locations of forewing and hindwing just passed by each other in plunging direction. The TEV on the forewing and LEV on the hindwing almost merged at this time instance. However, the fore- and hind- Wing III were still far from encountering. Therefore, the rigid hindwing caught the TEV of forewing earlier than the hind- Wing III model. Compared the combined LEV on the hindwings at $t/T = 0.48$, the LEV on the rigid hindwing got two cores while that on the hind- Wing III had only one core. One of the two cores came from the former LEV, while the other was obtained by combining the TEV from the forewing. This may be because that the relative positions of tandem wings offered better timing for the combination of the LEV and TEV. This additional core contributed to the lift generation of rigid hindwing. After $t/T = 0.48$, the two-core vortex on the rigid hindwing finally developed to become one-core vortex as that on the hind- Wing III.

The effect of deformation on the interaction was most significant at the 75% spanwise location. The rigid hindwing caught the shed TEV of forewing at $t/T = 0.44$ and fully made use of it to develop a strong LEV on the wing at later time instances $t/T = 0.48$ and 0.52 . However, due to the larger lags, the TEV on the fore- Wing III and the LEV on the hind- Wing III began to merge with each other at $t/T = 0.44$. However, the TEV and LEV did not combine. Instead, they remained contacted during $t/T = 0.48$ to 0.52 and then continued

to move to the opposite direction. All these led to lower lift generation on the hind- Wing III than the rigid hindwing.

According to the comparisons at three spanwise locations, it can be found that the rigid wings offered more beneficial relative positions for the hindwing to take advantage of the TEV of forewing. By merging the TEV of forewing more and earlier, the rigid hindwing obtained much higher peak than the hind- Wing III model.

The locations of hindwings in 90°-phased case from $t/T = 0.4$ to 0.52 were equivalent to those in single-wing configuration from $t/T = 0.65$ to 0.77 . Therefore, by comparing Figure 5.5 and Figure 5.12, the tandem effect at 90° phase difference can be found. For both the hind- Wing III and rigid wing, LEVs closer to the wing models were obtained with the existence of the forewings. However, the TEVs on the hind- Wing III and rigid wing were both weakened. Before the LEVs on the hindwings encounter the TEVs on the forewings, the much weaker TEVs on the hindwings should account for the lower lift generations when compared with the corresponding single-wing cases. For both the hind- Wing III and rigid wing, the shedding of LEVs were restrained by the forewings through $t/T = 0.4$ to 0.52 , which contributed to the lift generation. After $t/T = 0.44$, both the hind- Wing III and rigid wing made use of the TEVs of forewing, which also increased the lift generation. Therefore, unlike the single-wing case, the lift of hind- Wing III did not decrease after $t/T = 0.43$ and increased slowly instead. For the rigid wings, both the restraining of shed LEV and making use of the TEV led to fast increasing lift generation on it instead of the kink on the single-wing case, and finally to a extremely high peak.

Similar to the 0°-phased tandem-wing cases, the 90°-phased tandem-wing cases did not show much difference in the strength and location of LEVs on the

forewings when compared with the single-wing cases. As for the TEVs on the forewings, before they were caught by the LEVs of the hindwings, they were not changed much by the tandem effect either. So it is not necessary to present the flow fields of single forewings during $t/T = 0.4$ to 0.52 for comparison here. In this tandem-wing configuration, significant interaction between the TEVs on the forewings and the LEVs on the hindwings were observed, which should be supposed to change the force dynamics of forewings greatly. However, as shown in Figure 5.12, the angle of attack of forewings are close to zero during $t/T = 0.4$ to 0.52 . Therefore, even though the forewing and hindwings interacted greatly, the lift dynamics was not affected much, with the lift coefficients of both fore-Wing III and rigid wing close to zero.

5.1.4 Tandem-wing configuration at $\Psi = 180^\circ$

Similar to the 90° -phased case, the time axes for the forewings and hindwings at 180° phase difference in Figure 5.13 both start at the beginning of forewings' plunging motion. The tandem effect weakened the lift generation of fore- Wing III slightly during the deceleration periods of both up- and down- strokes, while decreased the lift of hind- Wing III significantly through almost the whole cycle. The lift of rigid forewing was decreased mainly during the beginning of deceleration periods. Different from the rigid forewing, the lift on the rigid hindwing was decreased by the tandem effect through almost the whole cycle. Generally, both 180° -phased tandem Wing III and rigid wings showed detrimental effect on the lift generations when compared with the corresponding single-wing cases. The tandem-wing configuration also modified the force dynamics. The kink on the downstroke of fore- Wing III was eliminated, while the secondary peak on the downstroke of hind- Wing III was weakened to be a kink. Interestingly, the tandem-wing configuration showed much more significant effect on the force dy-

namics of rigid wings than the Wing III models when compared with their corresponding single-wing cases. For the rigid forewing, the kink on the downstroke of single-wing case was also smoothed-out in the tandem-wing configuration. Moreover, the sharp high downstroke peak was replaced by a broad lower peak. Therefore, there was not much difference between the force dynamics of fore-Wing III and rigid wing during the downstroke. However, during the upstroke, quite different performance was obtained by the two models. The fore-Wing III obtained much higher upstroke peak than the rigid forewing. After $t/T = 0.22$, both the lifts of the fore-wing III and rigid decreased with larger lift obtained by the fore-Wing III. But the lift of the rigid forewing stopped decreasing at $t/T = 0.29$ and then generated a small peak, while the lift of the fore-Wing III kept decreasing all the way during the deceleration period. For the hindwings, similar situation also happened during $t/T = 0.22$ to 0.34 , as well as during $t/T = 0.68$ to 0.78 . At the beginning of these two periods, the hind-Wing III and rigid wing obtained similar lifts. Then the lift of the hind-Wing III kept increasing to reach the peak, while the lift of the rigid wing started to drop. However, during the deceleration period, the rigid hindwing obtained a small peak while the hind-Wing III did not. During $t/T = 0.68$ to 0.78 , the small peak was quite high that it was comparable to the secondary peak. Based on the results of the comparison in force dynamics, we focus the discussion on the comparison between the tandem Wing III and rigid wings during $t/T = 0.24$ to 0.36 in this tandem-wing case.

When the phase difference became 180° , the lags between the Wing III and rigid wings also existed. Similar to the 90° -phased case, the lags led to the modification on the relative positions of tandem Wing III models when the forewing and hindwing got close enough to each other (see Figure 5.11). Since the lag became larger when the location was further away from the root, the

Figure 5.13: Time histories of lift coefficients obtained by forewings and hindwings in tandem-wing configuration with phase difference of $\Psi=180^\circ$. The solid lines are the tandem-wing cases, while the dashed lines are the single-wing cases for reference. The differences between the tandem-wing cases and single-wing cases were marked as red-coloured and shaded areas for the Wing III and rigid wing models, respectively. The white and grey backgrounds represent the up- and downstrokes of forewings.

modifications of the relative positions of tandem wings were quite different at different spanwise locations. As shown in Figure 5.14, the locations of tandem Wing III and rigid wing models were compared at 25%, 50% and 75% spanwise locations to show the effect of flexibility on the interaction of tandem wings. At $t/T = 0.24$, before the forewings and hindwings encountered each other, the lags resulted in larger gaps between fore- and hind- Wing III models compared with the tandem rigid wings. The difference became larger when the location was further away from the wing root. At $t/T = 0.28$, the rigid forewing and hindwing had encountered each other and were moving away from each other. However, due to the lags, the fore- and hind- Wing III models just encountered each other at 25% and 50% spanwise locations, while were still far away from each other at 75% spanwise location. As the time went on to $t/T = 0.32$ and $t/T = 0.36$, the fore- and hind- Wing III models passed by each other. At these two time instances, the lags led to smaller wing gaps of tandem Wing III models at all three spanwise locations compared with the tandem rigid wings.

Figure 5.14. (i)

Furthermore, the wing gaps became smaller as the spanwise location approached to the wing tip.

Figure 5.14 presents the average velocity and vorticity fields for the tandem Wing III and rigid wings at $\Psi=180^\circ$ during $t/T = 0.24$ to 0.36 . The modification of relative positions showed different effects on the flow fields around the hindwings at 25%, 50% and 75% spanwise locations. At 25% spanwise location, the LEV on the hind- Wing III was slightly closer to the wing model than that on the rigid hindwing through $t/T = 0.24$ to $t/T = 0.36$ due to the lags. During this period, the modification on the relative positions at 25% spanwise location did not change much the interactions between the TEV on the forewing and the LEV on the hindwing. Until $t/T = 0.36$, neither the tandem Wing III nor the tandem rigid wings had their forewing's TEV and hindwing's LEV contacted.

(ii) $t/T=0.28$

Figure 5.14. (ii)

(iii) $t/T=0.32$

Figure 5.14. (iii)

Figure 5.14: (i)-(iv) Average velocity and vorticity fields for the tandem Wing III models and rigid wings at $\Psi=180^\circ$ during $t/T = 0.24$ to 0.36 .

At $t/T = 0.36$, the TEV on fore- Wing III model and LEV on hind- Wing III model got contacted, while the LEV on the rigid hindwing caught the shed TEV from the forewing.

At 50% spanwise location, in contrast to the situation at 25% spanwise location, the LEV on the rigid hindwing was closer to the wing model compared with that on the hind- Wing III. Compared with the 25% spanwise location, the differences between the relative positions of tandem Wing III and rigid wings became much larger. During $t/T = 0.24$ to 0.36 , the forewings and hindwings were plunging in opposite directions. As the forewing moving, a flow was induced to the upstroke direction and to the right side of it as shown in Figure 5.14. This flow acted on the LEV of hindwing directly at $t/T = 0.24$ and 0.28 . Because of the lags, the flow acted on the hind- Wing III was not as strong as that on the rigid hindwing. Therefore, the LEV on the rigid hindwing was induced to be closer to the wing model. After the forewings and hindwings encountered, at $t/T = 0.32$ and 0.36 , it was the TEV on the forewing that affected the location of LEV on the hindwings. Because of the lags between flexible and rigid wings, the tandem rigid wings got larger gap in plunging direction than the tandem Wing III models. Therefore, the TEV on the rigid forewing was more above the LEV on the rigid hindwing. So the flow induced by the TEV on the rigid forewing contributed to a closer LEV on the rigid hindwing. Finally, the rigid hindwing obtained closer LEVs through $t/T = 0.24$ to $t/T = 0.36$. Though the modification on the relative position at 50% spanwise location showed detrimental effect on the LEV's location on the hind- Wing III, it contributed to the lift generation of hind- Wing III in another way during $t/T = 0.32$ to 0.36 . It was observed that the TEV of fore- Wing III and LEV of hind- Wing III connected to each other during this period which would led to a lower-pressure region to create suction on the hindwing to

generate more lift. However, with larger gap, the TEV on the rigid hindwing failed to contact either the TEV on the forewing or the shed TEV. At both 25% and 50% spanwise locations, the TEVs on the hind- Wing III model were both stronger than those on the rigid hindwing through $t/T = 0.24$ to 0.36 . The stronger TEVs also contributed to the higher lift generation of hind- Wing III.

At 75% spanwise locations, the LEVs on the hind- Wing III and rigid wing were both almost lay on the wing model, with stronger LEVs on the hind- Wing III. The effect of different relative positions can be found when the fore- and hind- Wing III at 75% spanwise location just passed by each other. At $t/T = 0.32$, the rigid forewing and hindwing had become far away from each other. The rigid hindwing caught the TEV of forewing which was in front of it at this time instance. As time continued to $t/T = 0.36$, the TEV fully shed and fell on the LEV. However, the hind- Wing III failed to catch the TEV of forewing before it got shed due to the modified relative position. Different from the 25% and 50% spanwise locations, the 75% location had stronger TEVs on the rigid hindwing than the hind- Wing III through $t/T = 0.24$ to 0.36 .

At this phase difference, the factors affected the lift generations of hind- Wing III and rigid wing were complicated. For the hind- Wing III model, the closer LEV at 25% spanwise location, stronger LEV at 75% spanwise location, stronger TEVs at 25% and 50% spanwise locations, as well as more beneficial wing-wing interaction at 50% spanwise location all contributed to the lift generation of hind- Wing III. For the rigid hindwing, the closer LEV at 50% spanwise location, stronger LEV at 25% spanwise location, stronger TEVs at 75% spanwise location, as well as more beneficial wing-wing interaction at 75% spanwise location also offered benefits to the lift generation of rigid hindwing. But the combined effects on the Wing III model offered larger lift generation finally.

Comparing the force dynamics of hind- Wing III and rigid wing, the rigid wing got earlier drop in lift at $t/T = 0.22$, while the lift of Wing III started to decrease at $t/T = 0.27$. As shown in Figure 5.14(i), the lags led to larger wing gaps between tandem Wing III than the tandem rigid wings at $t/T = 0.24$, especially at 50% and 75% spanwise locations. As explained before, there were flows induced by the forewings towards hindwings when they were plunging close to each other. In this phase difference, the flow was very strong since the forewing and hindwing both approached the maximum plunging velocity before they encountered. On one hand, the flows induced the LEV closer to the hindwing. On the other hand, the flow also acted an additional 'negative lift' on the hindwing. With smaller gap, stronger flow was acted on the rigid hindwing to reduce the lift generation more, thus finally leading to earlier drop of the lift on rigid hindwing. After $t/T = 0.27$, both the lifts of hind- Wing III and rigid wing decreased due to the decreasing plunging velocity and angle of attack. At $t/T = 0.3$, the lift of rigid hindwing started to increase and obtained a small peak, while the lift on the hind- Wing III kept decreasing. From Figure 5.14 (iii) and (iv), it was observed that the LEV on the rigid hindwing at 75% spanwise location caught the TEV from the forewing and got enhanced, while the LEV on the hind- Wing III did not. This difference may account for the different lift dynamics during $t/T = 0.3$ to 0.36 , where rigid hindwing obtained a small peak while the hind- Wing III did not.

During $t/T = 0.24$ to 0.36 , the rigid forewing obtained force dynamics similar to the rigid hindwing. However, the mechanism is different from that of the rigid hindwing. Compared with the rigid forewing, the forewing of Wing III obtained stronger LEVs at all three spanwise locations through this period, but without obvious advantage in the location of LEVs relative to the wing model. For both fore- Wing III and rigid wing, the shedding of the LEVs can

be observed especially at 50% spanwise location. With the lags between the forewings of Wing III and rigid wing model in plunging direction, the shedding of LEVs on the forewing of Wing III was slightly restrained when compared with that of the rigid forewing. The stronger LEVs and the restrained shedding of the LEVs mainly account for the larger lift generation of the fore- Wing III than the rigid forewing through $t/T = 0.24$ to 0.36 . Before $t/T = 0.29$, the lifts of fore- Wing III and rigid wing both decreased because of the decreasing plunging velocity and angle of attack, as explained for the hindwings. At $t/T = 0.32$, the TEV on the rigid forewings combined with the LEV on the rigid hindwing at 75% spanwise location, as shown in Figure 5.14, which did not happen on the tandem Wing III. On one hand, the combined vortices enhanced the LEV on the rigid hindwing to increase the pressure difference between the upper and lower surfaces, thus generating additional lift. On the other hand, the combined vortices also enhanced the TEV on the rigid forewing, so that a lower-pressure region was generated on the lower surface of the forewing to generate additional lift. Therefore, a small peak was also generated by the rigid forewing.

5.1.5 Comparison between Wing III and Wing II

With appropriate flexibility, the Wing III models were found to outperform the rigid wings in both single-wing and tandem-wing configurations. However, the flexibility did not always offer benefit. As shown in table 5.1, the average lifts of Wing III, Wing II and Wing I decreased as the flexibility increased in all cases studied. With excessive flexibility, the Wing I models obtained dramatically lower lifts. By comparing the aerodynamic performance of Wing III and Wing II, how the redundant flexibility led to the reduction in the lift generation was investigated.

Figure 5.15 showed the time histories of the lift coefficients obtained by

Figure 5.15: Time histories of lift coefficients obtained by hind- Wing III and Wing II models in single-wing configuration. The white background represents the upstroke, while the grey background presents the downstroke.

the single Wing II and Wing III models for both the forewings and hindwings. During the acceleration periods on both up- and downstrokes, significant lags between the force traces of the Wing III and Wing II models can be observed, which mainly accounts for the lower average lifts of Wing II models. Moreover, more flexibility also led to lower up- and downstroke peaks of both fore- and hind- Wing II models. Comparing the force dynamics, it can be found that the two flexible wings obtained similar performance. The results of tandem Wing III and Wing II models were also compared in the previous study Zheng *et al.* (2015). The lags between force traces and similarity in force dynamics were also observed in the tandem-wing configurations. Therefore, the additional flexibility on the Wing II changed the aerodynamic performance mainly by leading to the lags between the force traces. To investigate how the additional flexibility resulted the lag between the force traces, the flow fields of single hind- Wing III and Wing II at $t/T = 0.2$ were investigated.

Figure 5.16 shows the deformation of hind- Wing II model, with the rigid hindwing as the reference, during the up- and downstrokes in single-wing configuration. The bending deformation of Wing II model was more significant

Figure 5.16: The deformations of hind- Wing II model (red) with rigid wing (blue) as reference in single-wing configuration at different time instances ($t^* = t/T$) during upstroke and downstroke.

than that of Wing III due to larger flexibility. The larger flexibility also resulted in slightly larger difference in angle of attack between the Wing II and rigid wing. However, the difference was still negligible since the Wing II model obtained only about 1.5° larger angle of attack than the rigid wing at mid-stroke location. As such, the main difference between the deformations of Wing III and Wing II was the lags relative to the rigid wing in plunging direction. With larger bending deformation, the lags for the Wing II were larger than the Wing III.

In Figure 5.17, the flow fields of Wing III and Wing II at $t/T = 0.2$ were compared. Similar flow structures were obtained by the hind- Wing III and Wing II at all three spanwise locations. In the comparison between Wing III and rigid wing (see Figure 5.4 and 5.5), the lag between the Wing III and rigid wing in plunging direction was able to restrain the shedding of the LEV on the Wing III. With larger lags in plunging direction, the shedding of the LEV on the Wing II at 25% and 50% locations was further restrained when compared with that of the Wing III, which contributed to the lift generation of the Wing II model. However, with more flexibility, the Wing II was too flexible to generate

Figure 5.17: Average velocity and vorticity fields for the single hind- Wing III and Wing II models at $t/T = 0.2$. Red solid lines indicate the positions of Wing III and Wing II models, while red dash lines are the corresponding positions of rigid wings for comparison.

the strong LEVs comparable to those of the Wing III. Especially at 50% and 75% locations as shown in Figure 5.17, the Wing II model obtained dramatically weaker LEV than the Wing III model. Moreover, slightly weaker TEVs were also found on the Wing II model at 25% spanwise locations. The weaker LEV and TEV finally led to the lower lift generation of Wing II. Similar effect can be also observed in the tandem-wing configurations, which resulted in the lower lift generation of tandem Wing II models than the tandem Wing III models.

5.2 Summary and conclusions

In this chapter, the dynamic performance of both flexible and rigid tandem wings in hovering flight at $Re_{\bar{U}_p} = 4,544$ was investigated. The dynamics of

lift generation was analyzed in details in single-wing configuration and tandem-wing configurations with phase differences at 0° , 90° and 180° . To uncover the mechanisms how the flexibility and phase difference affected the lift dynamics, 3D wing deformation and the flow fields obtained from the time-resolved PIV measurements were analyzed.

Both the phase difference and flexibility showed significant effect on the force dynamics. In the benchmark case, i.e. single-wing case, the flexibility offered benefits in lift generation with the lags in plunging direction. The lags restrained the shedding of the LEV and enhanced both LEV and TEV, which accounted for the better lift dynamics of single Wing III. In tandem-wing configurations, the forewings of both tandem Wing III and rigid wings were found to be able to make the LEVs on the hindwings closer to the wings, and restrain them from shedding as well. The flexibility in tandem-wing cases not only caused the lags but also the modifications in the relative positions of tandem wings. The modified relative positions affected both the strengths and locations of the LEVs on the hindwings. Especially in 90° and 180° -phased tandem configurations, the modified relative positions resulted quite different interactions of LEV on the hindwing and TEV on the forewing for the tandem Wing III and rigid wings. These effects resulted in the remarkable differences between flexible and rigid cases, as well as between tandem-wing and single-wing cases.

Chapter 6

Concluding remarks

Detailed conclusions have already been presented at the end of each chapter so that they will be only briefly summarized here. Moreover, the future work of this research study will also be discussed in this chapter.

6.1 Principal conclusions

The present research revolved around the experimental study on the aerodynamic performance of flexible tandem wings, i.e. Wing I, Wing II and Wing III, with the rigid tandem wings as the reference. The wing models were operated in both single-wing configuration and tandem-wing configurations at $\Psi = 0^\circ$, 90° and 180° . A hovering flight and two forward flights were investigated.

In chapter 3, the investigation focused on the aerodynamic performance of tandem rigid wings which aimed to offer further information to the forewing-hindwing interactions of the rigid tandem wings. The force and phase-locked PIV measurements were performed in both hovering and forward flights for the single-wing configuration and tandem-wing configurations with phase differences of 0° , 90° and 180° . The phase differences were found to affect the force generation significantly, especially on the hindwings, by leading to different peak values and phase lags between the force traces. 0° and 90° were the most favourable phase differences in hovering and forward flights, respectively. Different from most of previous studies which show that the tandem rigid wings

were worse than single rigid wing, the tandem rigid wing in the condition of current study outperformed the single wing in certain cases. The comparisons with the studies by Rival *et al.* (2011b) and Broering *et al.* (2012) showed that the differences in flow parameters such as Re and St and in wing motions might abruptly transit the results from “tandem wings better than single ones” to “tandem wings worse than single ones”. This result implies the possibility that better performance can be achieved by tandem wings as compared to single wing by modifying the flow parameters and wing kinematics. The phase-locked PIV measurements at the time instances of interest uncovered several mechanisms of the forewing-hindwing interactions. Among these mechanisms, the change in the location of LEV on the hindwing had not been identified in previous studies. Last, the comparison between the hovering and forward flights showed the remarkable effects of the incoming flow on the forewing-hindwing interactions, including shifting the LEV and TEV more downstream and modifying the flow between the forewing and hindwing. These effects have not been discussed before, which are supposed to contributed to the knowledge of tandem wings.

In chapter 4, the aerodynamic performance of flexible tandem wings were studied, with the rigid tandem wings as the reference. With appropriate flexibility, the tandem Wing III models showed advantages over the other wing models in the total horizontal force and efficiency in hovering and forward flights at $f = 1Hz$ ($St = 0.6$). 0° phase difference was found to contribute most to the horizontal force generation of tandem Wing III in these two flights. When the motion frequency decreased to $f = 0.5Hz$ ($St = 0.3$), it was the tandem Wing III, rigid wings and Wing II models that performed best at $\Psi = 0^\circ, 90^\circ$ and 180° , respectively. In this forward flight, the 90° phase difference offered greatest benefits to the tandem Wing III models. 2D deformation and phase-locked

PIV measurements were carried out to explain the differences in the force traces of tandem Wing III and rigid wings which included different peak values, phase lags and secondary peaks. The 2D deformation measurements showed that the flexible Wing III models lagged the rigid wings in plunging direction due to the bending deformation. Due to this lag, the LEVs closer to the wing models were generated by Wing III models which contributed to the higher horizontal force of Wing III models. What is more, a higher-velocity region near the hind-Wing III was induced by the fore-Wing III due to the lag in the forward flight, which was also beneficial to the horizontal force generation. The advantages of the flexible tandem wings over the rigid tandem wings shown in this chapter provided a new development direction for the MAVs.

In chapter 5, to further study the aerodynamic performance of flexible tandem wings, time-resolved PIV measurements were carried out at 25%, 50% and 75% spanwise locations of Wing III and rigid wing models to investigate the time evolutions of the flow structures based on the force dynamics. From the results of 3D deformation measurements, significant bending deformations were observed in both single-wing and tandem-wing cases. In addition to the lags of Wing III models relative to the rigid wings in plunging direction, the bending deformation also caused the modifications in the relative positions of the forewing and hindwing on the tandem Wing III models. Comparing the flow fields of single hind-Wing III and rigid wing, the lags led to stronger LEVs on the hind-Wing III and restrained the shedding of the LEVs, which finally resulted in quite different lift dynamics of hind-Wing III and rigid wing. In tandem-wing configurations, with the lags in plunging direction and modifications in relative positions, the induced flows of fore-Wing III model and rigid forewing showed very different effects on the strength and location of the LEVs and TEVs on the hindwings. Furthermore, the interaction of LEV on the hind-

wing and TEV on the forewing was also modified due to the changes in relative positions of forewings and hindwings, especially in 90° and 180° -phased tandem-wing configurations. In the previous studies on the flexible wings, the chordwise deformation is found to decrease the effective angle of attack so that the LEV stall is delayed (Hu *et al.*, 2008; Kim *et al.*, 2009; Heathcote & Gursul, 2007). This effect helps to stabilize the LEV, which enhances the lift generation. In the present study, the spanwise deformation resulted in a lag in plunging motion of flexible tandem wings as compared to the rigid tandem wings. For both the rigid and flexible wings, the LEVs shed behind the wing model as they plunged forward. Since the flexible wing lagged behind the rigid wing, the LEV which was being shed became closer to the flexible wing model. In this way, the shedding of LEV was restrained. Similar to the delayed stall effect caused by the chordwise flexibility, the restrained shedding effect also contributed to more stable LEV and enhanced the lift generation. In this chapter, the effects of bending deformations on the force dynamics of tandem wings offer new perspectives for the forewing-hindwing interactions of tandem wings. Furthermore, the results also indicate that the bending deformation show great potential in flight control of tandem wings, which inspire new methods of stability control for the tandem-wing MAVs.

Generally, the advantages of flexible tandem wings in aerodynamic force generations and force efficiency, as well as their potential in flight control, are both expected to contribute to the development of MAVs. Moreover, the current study also provides the experimental results to the future numerical work for validation.

6.2 Future work

Although this study presented the flow fields at different spanwise locations obtained from both phase-locked and time-resolved PIV measurements, our two-dimensional PIV data are still limited since the vortical structures around the tandem wings are three dimensional. As such, our future work will try to explore the three-dimensional flow topologies of the flow structures using tomographic PIV measurements (Lee & Wu, 2013*a,b*; Tang *et al.*, 2014; Wu *et al.*, 2015; Lee & Wu, 2015) to provide further information on the forewing-hindwing interactions.

As shown in chapter 3 and 4, the aerodynamic performance in hovering and forward flights showed quite different results for either the rigid or flexible tandem wings. However, due to the limitation of equipments, the time-resolved PIV measurements in chapter 5 were carried out only in the hovering flight. It should be also meaningful to investigate the dynamic performance of the tandem wings in the forward flight in the future work.

Besides the aerodynamic forces and efficiency, the flight stability also plays an important role in MAV-motivated flight systems design. The stability problem is challenging due to the complicated 6-degree of freedom and unsteady flapping motion. Moreover, the unsteady fluid-structure interactions of flexible-wing MAVs also make the stability control difficult. The real insects achieve precise flight stability by rapid and continuously varying the wing kinematics. Inspired by the real insects, more studies on the flying kinematics and motion control system are required. In Chapter 5, the bending deformations show great effects on the force dynamics, which is also of considerable interest to the stability control.

In nature, the wings of real dragonflies have a lot of vein structures and show significant twisting deformation in the flapping motion. Previous studies have

shown that the vein structures and chordwise deformation would contribute to the aerodynamic performance of flexible wings. Therefore, it is of meaning to concern veined structure in the future study on the aerodynamic performance of flapping wing, as well as the MAV design.

Publications arising from this thesis

Journal papers

1. Zheng, Y., Wu, Y. & Tang, H. 2016 An Experimental Study on the Forewing-hindwing Interactions in Hovering and Forward Flights. *International Journal of Heat and Fluid Flow* **59**, 62-73.
2. Zheng, Y., Wu, Y. & Tang, H. 2016 A Time-resolved PIV Study on the Force Dynamics of Flexible Tandem Wings in Hovering Flight. *Journal of Fluids and Structures* **62**, 65-85.
3. Zheng, Y., Wu, Y. & Tang, H. 2015 Force measurements of flexible tandem wings in hovering and forward flights. *Bioinspiration & Biomimetics* **10** (1), 016021.

Conference papers

1. Zheng, Y. & Wu, Y. 2015 Aerodynamic performance of flexible tandem wings in hovering flight. 3rd Symposium on Fluid-Structure-Sound Interactions and Control, Australia
2. Zheng, Y. & Wu, Y. 2014 Measurements of aerodynamic forces and wing deformation of flexible tandem wings. The 2nd Asia-Pacific Conference on Life Science and Engineering, Taiwan
3. Zheng, Y. & Wu, Y. 2014 Force Measurement of flexible tandem wings in hovering flight. International Conference on Information Technology and

Engineering (ICTAE), Hong Kong. Best paper award

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Author's biography

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