Experiments on the merged vortex formation in a flapping plate

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Abstract. A two-dimensional flapping device was designed by consisting of a front flapping flat plate and a rear fixed horizontal plate in a rectangular tunnel. The flow characteristics near the plate and the downstream were studied under different flapping parameters. A high-speed camera was used to obtain the flow images to analyse the shedding vortex formation. Results show that a merged vortex is generated when the plate flaps and, relatively, an inertial vortex is generated when it stops. The vortex merger is in agreement with the Kovaznay model after the non-dimensional time $t/T$ of 0.3, implying its non-equilibrium properties during energy transfer. The length-scale ratio of the merged vortex to the neighbour existing minor vortex is around 2, providing an experimental verification for the simulations of Cardesa et al. [Science 2017]. In addition, the most clear merged vortex is formed when the plate flaps between 30 and 60 degree at a tip flapping linear velocity 3 times bigger than the inlet flow velocity.

1. Introduction
Since ancient times, humans are always eager to fly like a free bird. With the flapping wing flight becoming a technical hotspot in the aircraft development [1], there have been an increasing number of researches for investigating the flapping wing flights. In 1998, the first electrically powered palm-sized ornithopter “Microbar” was successfully developed, being capable of turning left or right and pitching up or down [2]. In 2008, Wood [3] developed a flapping-wing micro-robot, which can produce sufficient thrust to accelerate vertically. In 2012, a revolutionary design “Smart Bird”, with an ingenious transmission mechanism and a precise control system, can fold and reverse the wings to have good aerodynamic performance [4].

Compared with the flapping-wing prototype, the theory of the flapping wing flight also has a rapid development because of the progress of experimental techniques and numerical simulations. Pomphrey et al. [5] have studied the mosquitoes flapping wing kinematics, arguing three key features: leading edge vortices, trailing-edge vortices caused by a form of wake capture at stroke reversal, and rotational drag. André and Jacquin [6] have presented 2D direct numerical simulations at Reynolds number $Re = 1000$. They analyzed three fundamental mechanisms, suction by the leading edge vortex, added mass reaction and wake capture. Chandra and Damodaran [7] have proved that the thrust is generated as a result of vortex asymmetry and the relative convection rates of positive and negative vortices are a key parameter involved in thrust generation. Taylor et al. [8] have confirmed that a
general principle of oscillatory lift-based propulsion for flapping wing flight seems to be tuning cruise kinematics to optimize St Number.

Most of the existing studies indicate that flapping wing flight is based on the vortex formation and dissipation around the wing. But now it lacks of a convincing explanation for the vortex formation and dissipation of the flapping wing, which relates to complicated turbulence theory on vortex formation and dissipation. Indeed, visible observations of the Kolmogorov-Richardson energy cascade [9-11] have confused researchers for quite long time, until the very recent study by Cardoza et al. [12], which successfully simulated the process that energy is transferred from large to small vortices with accurate quantitative descriptions. However, to our knowledge, there is still no experiment for verifying this important numerical advance.

In this contribution, in order to clarify the vortex formation of the flapping wing flight with comparison to theoretical predictions, the question is simplified as the vortex formation of a flapping plate. A two-dimensional flapping device is designed to help to better understand the formation and underlying mechanisms of the vortices.

2. Experimental set-up and calibration

As shown in Fig.1, a two-dimensional flapping device is designed, consisting of a front flapping plate and a rear fixed horizontal plate in a Plexiglas rectangular tunnel. The flapping plate is driven by a stepper motor and the fixed plate is fixed by a square shaft. The flapping and fixed plates are located at 120 mm height in z direction. The rectangular Plexiglas tunnel is 50 mm width in y direction and 200 mm height in z direction. The flow images are obtained by an IDT's X-Stream VISION XS-3 high-speed camera whose full-angle pixel is 1280 × 1024, the maximum frequency is up to 10000Hz and the minimum exposure time is down to 1μs.

![Figure 1. Experimental set-up](image)

The flapping plate flaps clockwise from the initial angle to the end angle, and returns to its original position. An initial angle is defined as the angle at which the plate starts to flap. An end angle is defined as the angle at which the plate stops and changes its flapping direction. Thus, a flapping angle is defined as the difference between the initial and end angle. Regarding the x direction as 0 degree, three kinds of flapping angle are set, including the difference between 0 and 90 degree, between 30 and 90 degree and between 30 and 60 degree.
Because of the system response delay and the manufacturing error, the real tip flapping velocity of the plate is different from the set velocity. The real tip flapping linear velocity is measured by the high-speed camera. As shown in Fig.2, the scatter curves present the real velocity, while the line curves present the set velocity. The inlet flow velocity is about 0.25 m/s, so the velocity ratio $\varphi$ of the flapping velocity $\omega R$ to the inlet flow velocity $v_0$, $\varphi = \omega R / v_0$, ranges from 3 to 4.6.

![Figure 2. The calibration of the tip flapping linear velocity](image)

3. Results and discussion

3.1. Shedding vortex formation

A merged vortex is defined as the vortex merged by several minor vortices. A minor vortex is defined as the existing small vortex, which is neighbor to the merged vortex and will be merged in the future. Fig.3 (a), (b) and (c) show that when the plate flaps from the initial angle, the streamline is bent and the minor vortices are generated and shed alternately on the tip of the plate. Subsequently, the minor vortices merge as a merged vortex. Larger than 60 degree, few minor vortex is generated while the merged vortex keeps expanding and eventually turn into the largest merged vortex. During the entire clockwise flap, the vortices are attached to the trailing edge of the plate.
Figure 3. Vortex formation ($\varphi=4^\circ$ and between 0 and 90 degree)

During the short pause between the clockwise and counterclockwise flap, a reversely rotatory inertial vortex is generated in the other edge of the plate in Fig.3 (e). Meanwhile the merged vortex is squeezed, with the length-scale decreasing as shown in Fig.3 (f). The inertial vortex and the merged vortex seem to behave as a pseudo asymmetric vortex pair.

When the plate returns to the initial angle counterclockwise from the end angle, the pseudo asymmetric vortex pair shed from the tip of the plate. Then a minor vortex is generated and sheds into the neck of the pseudo asymmetric vortex pair quickly. This new minor vortex rotates fast as a vortex core, squeezing and breaking the inertia vortex and the merged vortex as shown in Fig.3 (g). The pseudo asymmetric vortex pair are destroyed totally and a second merged vortex is formed relatively. Compared with the minor vortices in the clockwise flap, some minor vortices in the counterclockwise flap not only shed individually without merger, but also depart from the plate. As presented in Fig.3 (h), these minor vortices appear in the area where the tip passes through and remain substantially in place for a short time like a string of pearl necklaces.

Fig.3 (i) indicates that once the plate returns to the initial angle, there will be a second inertial vortex on the tip. In addition, the air near the trailing of the fixed horizontal plate is oscillated continuously during the whole flap, thus a trailing vortex is regularly generated and sheds later.

It could be concluded that the flapping plate generates a merged vortex every direction flap. There is a possible reason that the flap creates a pressure distribution, which takes an important role in the vortex formation. The air is driven by the differential pressure to roll up, which develops as the merged vortex eventually. Due to the inertia, even though the plate stops, the upstream air still maintains its original movement, forms a velocity shear layer and then generates an inertial vortex.
3.2. Vortex merger

As mentioned above, the minor vortices merge as the large merged vortex. From the viewpoint of turbulent energy transfer, this inverse energy cascade is a typical two-dimensional phenomenon, which supports the quasi-two-dimensional design of the present experiment. In order to quantitatively describe this, we introduce the classical Kovaznay model, which provides an understanding of the local non-equilibrium time between scales [13, 14]. The relation between the non-equilibrium time $t$ and the length-scale $l$ during the vortex merger is

$$\log(l) \sim \frac{3}{2} \log(t)$$  \hspace{1cm} (1)

Because most of the vortices are irregular, the length-scale $l$ of a given vortex is measured as the average of the length of the vortex in the direction parallel to the plate and the length in the direction perpendicular to the plate. The non-dimensional length-scale $l/l_L$ is defined as the ratio of the length-scale of the merged vortex to the length-scale of the final largest merged vortex. Time $t$ is calculated from the plate start to flap. The non-dimensional time $t/T$ is defined as the ratio of the present merger time to the time the merged vortex formation finally spends. Fig.4 (a) shows the comparison between Kovaznay model and our result. It is obvious that results are in quite good agreement with the model after a non-dimensional time $t/T$ of 0.3 (corresponding to $\log(t/T) > -0.5$). To explain this fact, we recall that the non-equilibrium time describes a local time-scale that turbulence tends to equilibrium [15]. This then implies that vortex merger can be considered as a non-equilibrium phenomenon, which is also in agreement with the fact that energy backscatter is a typical non-equilibrium turbulence transfer [16]. For smaller time scales, this non-equilibrium scaling is not satisfied in Fig. 4(a), which might correspond to the experimental difficulty that small vortices are difficult to be accurately measured.

**Figure 4.** Change of the length-scale along the time in the vortex merger

Simulation results of Cardesa et al. [12] also suggest that in an inverse energy cascade, vortices of a given length-scale originate from the vortex of half their scale. A non-dimensional length-scale ratio is then defined as the ratio of the non-dimensional length-scale of the merged vortex to that of the minor vortex. In Fig.4 (b), the non-dimensional length-scale ratio is presented along the time. It is in general around the expected value 2, which provides an experimental verification for the simulation results of Cardesa et al.
3.3. Influence of the flapping velocity and angle

According to a previous report result [8], there is a suitable range of the flapping velocity for a given inlet flow velocity and a given plate size that makes the merged vortex structure most clear. Too high flapping velocity not only cannot effectively generate a merged vortex, but also brings a too strong perturbation to the flow field, causing a wide range of turbulence pulsations. In our experiment, the best velocity ratio $\varphi$ of the flapping velocity to the inlet flow velocity varies from three kinds of flapping angle. Fig.5 indicates that it is about 4.6 for 90 degree, 3.4 for 60 degree and 3 for 30 degree. From the view of energy input, a bigger flapping angle involves a larger area of air, requiring a more increasing energy input, which refers to a much higher velocity.

![Figure 5. Comparison between four kinds of flapping velocity](image)

If the plate flaps between 30 and 90 degree, a significant difference is that the second inertial vortex is hardly observed. Sometimes even the trailing vortex only has an unclear structure. The second inertial vortex and the trailing vortex seem to be inhibited by the plate, which stops at 30 degree as shown in Fig.6 (b).

If the flapping angle reduces to a small range between 30 and 60 degree, the merged vortex, involving 2 or 3 minor vortices, is quite fuzzy until the plate tends to stop at the end angle. Besides, an exciting phenomenon is that the second merged vortex shows an obviously clear vortex structure, involving just a few minor vortices as shown in Fig.6 (c). Confusingly, several trailing vortices appear again on the upper surface of the fixed plate instead of the trailing edge. Probably, those trailing vortices are not the trailing vortices mentioned in 90 degree flapping angle, but the minor vortices generated in clockwise flap. It is such a small angle that the vortices cannot cross the tip in a limited time.
Figure 6. Comparison between three kinds of flapping angle at $\varphi = 3.4$ (a) between 0 and 90 degree; (b) between 30 and 90 degree and (c) between 30 and 60 degree.

By adjusting the flapping angle, the inertial vortices and the trailing vortices can be inhibited. It may be explained by that the plate, which stops at 30 or 60 degree, can play a guiding role. The plate changes the air movement relative to the inlet flow from orthogonal to oblique, which weakens the velocity shear layer strength in some extent.

**Conclusion**

The present contribution investigates the merged vortex formation in a flapping plate, aiming at providing new understandings of the merged vortex. A two-dimensional flapping device is designed, which enables the plate to flap at a tip flapping velocity 3 to 4.6 times bigger than the inlet flow velocity. Main results from this work are listed as follows:

1. The flapping plate generates practically a merged vortex, which merges with several minor vortices, by creating a low-pressure area upstream to drive the air to roll up and an inertial vortex when stops.

2. The vortex merger follows the Kovaznay model after the non-dimensional time $t/T$ of 0.3 and the non-dimensional length-scale ratio of the merged vortex to the minor vortex is around 2, implying that the vortex merger is a non-equilibrium phenomenon.

3. The clearest merged vortex is formed when the plate flaps between 30 and 60 degree at a tip flapping velocity 3 times bigger than the inlet flow velocity, maintaining enough energy input and inhibiting the inertial vortex and the trailing vortex formation.

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