Flow Field Characteristics and Lift Changing Mechanism for Half-Rotating Wing in Hovering Flight

Q Li, X Y Wang, H Qiu, C M Li and Z Z Qiu

School of Mechanical Engineering, Anhui University of Technology, Ma’anshan, 243002, P.R.China

liq_ahut@163.com, wangxy@ahut.edu.cn, qiuhan@ahut.edu.cn, licongmin_ahut@163.com, qzzhlx@ahut.edu.cn.

Abstract. Half-rotating wing (HRW) is a new similar-flapping wing system based on half-rotating mechanism which could perform rotating-type flapping instead of oscillating-type flapping. The characteristics of flow field and lift changing mechanism for HRW in hovering flight are important theoretical basis to improve the flight capability of HRW aircraft. The driving mechanism and work process of HRW were firstly introduced in this paper. Aerodynamic simulation model of HRW in hovering flight was established and solved using XFLOW software, by which lift changing rule of HRW was drawn from the simulation solution. On the other hand, the development and shedding of the distal vortex throughout one stroke would lead to the changes of the lift force. Based on analyzing distribution characteristics of vorticity, velocity and pressure around wing blade, the main features of the flow field for HRW were further given. The distal attached vortex led to the increase of the lift force, which would gradually shed into the wake with a decline of lift in the later downstroke. The wake ring directed by the distal end of the blade would generate the downward accelerating airflow which produced the upward anti-impulse to HRW. The research results mentioned above illustrated that the behavior characteristics of vortex formed in flow field were main cause of lift changing for HRW.

1. Introduction

The movement forms of animal limbs are asymmetric swing motion in essence[1]. Swing is just a movement form that adapts to muscles for animal, whereas the asymmetry of motion is the basic condition to fly and walk. Flapping Wing Air Vehicle (FWAV) has been a topic of considerable interest for its wide application in military and civil fields[2-3]. Particularly, rich results had been got in FWAV aerodynamic research[4], such as theoretical modeling, lift experiments in different conditions and numerical simulation based on Computational Fluid Dynamics (CFD) theory. However, one insurmountable obstacle in the research for the development of FWAV in large size is the difficulty in overcoming the large inertial force generated when the flapping wing reciprocate and swing in a high speed[5]. Thence, our work team had developed a rotating mechanism named Half-Rotating Mechanism (HRM)[1], which could not only produce asymmetrical motion but avoid swing. HRW flight mechanism was reasonably developed to make HRW aircraft in large size possible.

The research on changing mechanism of the flight lift for Half-rotating Wing (HRW) is significant to determine the flight capability of HRW aircraft. The airflow on the airfoil of HRW is complicated, and the vortice formed in the flow field is the main source of lift changing for HRW. In this paper, the
influence about the generation and variation of vortex of the blade on lift force for HRW was given by using the CFD software XFlow as the blade was rotating. According to the aerodynamic force of HRW and the airflow near the airfoil, deeper research on the lift characteristics of HRW was conducted to reveal its lift changing mechanism.

2. Driving mechanism and work principle of HRW

2.1. Driving mechanism of HRW

The driving mechanism of HRW was a kind of simplified HRM which was suitable for flight[6]. As shown in figure 1, point C was not only the center of shaft with groove but also the middle of blade of HRW. Point H denoted the center of positioning slider, which was the fixed point in HRM. HRW could produce continuous and certain motion when motor drove the crank to rotate. The blade of HRW would turn half round anticlockwise when crank turned one round anticlockwise, accordingly resulting in the asymmetric rotation.

2.2. Work process of HRW

The blade of HRW, a working component driven by the crank, did the plane movement which could be decomposed into the translation following with shaft C and the rotation turning around point C. As shown in figure 3, AB represented the blade of HRW whose span and chord length were respectively 2a and h, while OC represented the crank whose length was R. The angular velocity of HRW was \( \omega/2 \) when the angular velocity of crank was \( \omega \). \( \phi \) was indicative of the rotation angle of crank from original position where crank was in direction of horizontal-right while the rotation angle of HRW was \( \phi/2 \). Our work team had developed a HRW aircraft prototype, which was symmetrically arranged with double blades as shown in figure 4. In this text, the simulation model was in reference of the prototype whose dimensions were \( R=0.06m, 2a=0.28m, \) and \( h=0.21m \).

3. Lift changing rules and flow field characteristics of HRW
3.1. Lift changing rules of HRW

The computing model of HRW was established based on software XFlow. The flight working condition was set as no incoming flow, namely it was in hovering flight, while $\omega$ was set as $20\pi$ rad/s. Figure 5 showed the time history of lift for HRW in 0.5s.

![Figure 5. The time history of lift for HRW at $\omega=20\pi$ rad/s](image)

Figure 5. The time history of lift for HRW at $\omega=20\pi$ rad/s

Obviously, lift changed in cycle, and each stroke reached a force peak in the middle phase. At the onset of wing rotation, the lift began to rise slowly, and then reached a peak (to approximately 2.5-2.75N) followed by a relatively rapid decline. Moreover, the forces generated in the first stroke were similar to those generated during later strokes, with one distinct difference that the force peak in the first stroke was larger than later strokes.

3.2. Airflow changing rules of HRW in the flow field

Due to the different flapping mode of the blade, the lift curve of HRW was not consistent with the lift curve measured by Dickinson in Drosophila melanogaster experiment[7]. Therefore, the characteristics of the airflow near the blade were analyzed to research the relationship between the lift force and the changes of the flow field. The cross-section was created at midchord of the blade in the XFlow post-processing project tree. By gathering a complete time history of fluid velocity through five strokes, we could observe the growth of vorticity in select regions around the blade throughout each stroke. As shown in figure 6, HRW was started to rotate in the stationary flow field, and the plot of velocity at six moments in the first cycle was selected to analyze. The red point in the figure was the modeling center in XFlow, which was on the horizontal right side of the fixed point $H$, and the distance between them was 0.09m.

![Figure 6. Velocity diagram of HRW during the first stroke](image)

Figure 6. Velocity diagram of HRW during the first stroke

Vortex was mainly generated at the ends of the blade when HRW hovered in the air. In this paper, the end which was farther away from fixed point of the blade, namely the left end of the blade in figure 6, was called the distal end. Similarly, the right end of the blade could be called the close end. Hence, the vortex at the distal end of the blade was called the distal vortex(DV), and the other was
called the close vortex(CV). Likewise, the vortex with the characteristic of attaching to the blade was called the attached vortex(AV), and the vortex which was staying at the blade was called the resident vortex(RV).

As shown in figure 6, at \(t=0.01s\), the blade began to rotate in counter-clockwise direction, while the clockwise AV appeared at both ends of the back flow side of the blade with concomitant increase in force. Moreover, the fluid stationary state in the original equilibrium space was instantly broken by the movement of the blade and then a lift pulse was yielded. Therefore, the lift peak of the first cycle was higher than later few cycles as shown in figure 5.

At \(t=0.03s\), the increase in force, which we attributed to acceleration-reaction movement of the distal end of the blade, occurred as the AV at the distal end significantly grew. Whilst the reverse AV at the close end was shed, leaving the RV rolled in the same direction as the blade. Accordingly, the rotational circulation rotated with the blade was produced by the RV, changing the direction of the near-wing airflow, whereas the angle between the airflow and the blade was increased. Thereby the speed which was parallel to the blade was reduced, reducing the ability of pushing the DV out of the blade so that the DV would not shed so quickly. This prolonged attachment of the DV led to the increase in lift force.

With continued rotation, the DV was not shed until the blade was close to the horizontal position, namely it turned over 90° at \(t=0.05s\). There were some flowing fan-shaped areas between the vortex and the rotational circulation that were consistent in orientation and size, which were called stream[8]. Such streams were often generated between vortices or vortex and surface of object. The changes of momentum of these streams would yield forces reverse to the movement of the streams on the surrounding related objects. These forces would produce moments that blocked the rotation of the blade and simultaneously yielded upward lift force against the streams. At this time the contact area of the blade and the streams was the largest, resulting in the lift peak.

From \(t=0.07s\) to \(t=0.09s\), the DV was slowly shed while the RV was not shed during the whole stroke. At this time the contact area between the blade and the streams was small, so the lift value gradually decreased until the lift force was down to 0 by \(t=0.10s\).

3.3. Distribution characteristics of vorticity, velocity and pressure for HRW in the flow field

The distribution characteristics of vorticity, velocity and pressure in the flow field would be further comprehended by the cloudatlas to analyze the flow field characteristics for HRW. Figure 7 showed the vorticity, velocity and pressure cloudatlas near the blade of HRW in the fourth stroke.

It was found that at \(t=0.01s\), the AV at the distal end of the blade was formed with the wake directed by the close end generated in the prior two strokes underside of the blade in the vorticity cloudatlas. The velocity of flow in the center of wake was considerably larger in the velocity cloudatlas. The high pressure area was on the incoming side of the distal end of the blade, whereas the pressure of the back side was low in the pressure cloudatlas, resulting in the generation in force.

At \(t=0.03s\), the AV at the distal end was increased. The wake at the close end was elongated while the early wake was faded in the vorticity cloudatlas. In the velocity cloudatlas, the large flow velocity area at the distal end was increased, whereas the influence of the early wake was weakened. The high pressure area and the negative pressure were both enlarged in the pressure cloudatlas, leading to the increase in lift force.

At \(t=0.05s\), the AV at the distal end reached maximum, and the induced effect of the close end was getting weaker in the vorticity cloudatlas. In the velocity cloudatlas, the large flow velocity area of the AV at the distal end was continued to increase while the range of the wake area was enlarged but the flow velocity was decreased. The high pressure area on the incoming side was even bigger and the negative pressure area was also enlarged in the pressure cloudatlas, leading to the increase in lift force.
Figure 7. Vorticity, velocity and pressure cloudatlas for HRW in the fourth stroke
At \( t = 0.09 \) s, the AV at the distal end was shed and rolled up into a new wake, and the wake was detached from the close end in the vorticity cloud. In the velocity cloud, the range of the distal large velocity area was increased but the intensity was weakened. The high pressure area was big but the intensity was weakened, whereas the negative pressure area was smaller so that the lift force was lower in the pressure cloud.

At \( t = 0.10 \) s, the next stroke would begin and simultaneously the distal end and the close end would be swapped, resulting in a new distal AV and a large flow velocity area. The incoming side and the back side was swapped while the pressure direction was constant.

4. Lift changing mechanism for HRW

The elevated aerodynamic performance of insects has been attributed in part to the generation and maintenance of a stable region of vorticity\[9\]. The negative pressure on the surface of the blade would be improved if the blade was affected by the high-speed rotational vortex, leading to a great lift force. By analyzing the simulation results, the main features of the flow field for HRW were obtained. The change of velocity, pressure and lift was derived from the unique vortex, wherefore the lift changing mechanism for HRW was further analyzed on the basis of the characteristics of the vortex in this section.

4.1. Changes of the distal vortex

The vortex of HRW was first generated on the distal end of the blade, and then became gradually stronger and larger. Subsequently in the period of \( 0.05 - 0.07 \) s, the vortex was shed from the blade but still linked with it, forming the gradually expanding vortex ring directed by the distal end of the blade. Figure 8(a) and 8(b) were respectively the three-dimensional graphs of the vorticity in the flow field for HRW in the first and fourth strokes at \( t = 0.07 \) s, and the lower blade end was the distal end and another blade end was the close end.

Figure 8. Vortex ring at both ends of the blade

Figure 8(a) was corresponding to the moment \( t = 0.07 \) s in figure 6. It was obvious that the AV whose both sides were still connected with the blade after it shed from the distal end of the blade formed a small vortex ring which was gradually grew under the guidance of the end of the rotating wing. And then it formed the wake towards the underside of the blade in the later half stroke. The airflow in the vortex was upward outside and downward inside so that the downstream accelerating airflow which was namely the airflow in the stream area in section 2.2 was formed in the middle of the vortex ring. This stream had a more obvious reflection in the fish parade\[10\]. The wake left behind the tail of swimmers was a staggered array generated as the caudal fin moved back and forth. A jet flow with alternating direction between the vortices would produce hydrodynamic force to push the fish forward. The structure of the wake was of a thrust-type, had a reversed rotational direction compared to the well-documented drag-producing Karman vortex street. Thus, HRW could still obtain upward lift by generating the downward accelerating air after the DV was shed.

Figure 8(b) was corresponding to the moment \( t = 0.07 \) s in figure 7. The long arc-shaped wake, which connected to the close end as shown in the bottom of the figure was formed below the blade after the distal AV of the prior stroke was shed.
4.2. Effect of the wake ring on airflow
The airflow in the vortex ring of the wake was upward outside and downward inside so that the downward accelerating airflow was formed in the middle of the vortex ring in figure 8(b). At the same time the incoming surface of the blade pushed the fluid forward, which was the driving force to accelerate the airflow. Accordingly, a directional airflow mass which flew rapidly downwards was formed in the flow field toward the bottom under the collective effect between the blade and the wake. Furthermore, the airflow could be pushed in all directions by the rotating blade but the wake was always located below the horizontal position of the blade. Consequently, most of the airflow pushed by the blade was moved downward through the wake ring.

The downward momentum of the airflow mass was added during the process of being driven by the blade and guided by the wake ring, so it was subjected to a downward impulse and produced the upward anti-impulse to the outside. Since the airflow was primarily pushed by the blade, the anti-impulse would affect on the blade. The high pressure area displayed on the incoming surface of the blade in figure 7 was the acting result of the anti-impulse, leading to the lift force of HRW.

4.3. Lift changing mechanism for HRW
It was indicated that the generation and attachment of the distal vortices on the blade caused the gradually increasing lift force by analyzing the aerodynamic and flow field characteristics for HRW. In the later downstroke, the distal vortex was still associated with the blade when it was shed, forming a vortex ring which was gradually enlarged under the guidance of the distal end. The lift force was still generated by the downward accelerating airflow in the middle of the vortex ring. However, the lift would gradually declined because of the decreasing contact area between the accelerating airflow and the blade.

After the start of the next stroke, the close end of the blade was changed to the distal end. As the continuous increase in the distal end velocity, the new AV was formed at the distal end with the increase in lift force in cycle. Moreover, the wake area was formed below the blade after the distal AV of the previous cycle was shed, and the upward anti-impulse which played a certain role on the increase of lift for HRW was produced by the downward accelerating airflow in the middle of the wake ring.

5. Conclusions
1) Aerodynamic solution showed that lift of HRW changed in cycle in hovering flight, and each stroke reached a force peak in the middle phase. Moreover, the changing rules of the lift force were consistent with the flow field characteristics of HRW.

2) The distal attached vortex produced by the rotation of the blade led to the increase of the lift force, while in later downstroke it gradually fell off from the blade with a decline of lift and then became the wake of the next stroke. The downward accelerating airflow generated in the middle of the wake ring produced the upward anti-impulse to HRW, which played a certain role on the increase in lift for HRW.

3) Distal vortex and wake ring formed by the shedding of distal vortex in the flow field were main source of the lift force for HRW during hovering flight.

Acknowledgments
This work is supported by the National Natural Science Foundation of China (Grant No. 51375014)

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