Numerical calculations on the flow near the plunging airfoil and relation with the flying or swimming animals, birds, fish and insects

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Abstract
We investigated the influence of the airfoil geometry on the performance of the plunging airfoil numerically. In the present study, two circular arc airfoils with the different thickness were used and the numerical calculations were carried out within the laminar flow region to obtain the data of the extremely small micro air vehicles. Moreover, the arbitrary Lagrangian-Eulerian method was adopted to solve the moving boundary problem. The calculation results are summarized as follows. (1) The thickness of the airfoil has a strong effect on the lift and thrust forces, and these forces for the thick airfoil are insensible to the change in the angle of attack compared with the ones for the thin airfoil. (2) The optimal oscillating frequency of the plunging airfoil has a strong relation to the conditions of the flying or swimming animals, birds, fish and insects.

Key words: Bio-fluid mechanics, Moving boundary problem, External flow, Computational fluid dynamics, Fluid force

1. Introduction

In recent years, micro air vehicles (MAVs) have attracted the interest of many researchers owing to a great number of the application fields and MAV projects have been initiated in many countries (for example, Pines and Bohorquez, 2006). It is clear that the MAVs operate in a low Reynolds number region compared with the ordinary air vehicles. So, the effective thrust and lift generation mechanism under the strong viscous effect due to a low Reynolds number will be required for the development of the MAVs. For this reason, many theoretical and experimental studied have been carried out and the plunging airfoil began to attract the attention of many researchers gradually (Lai and Platzer, 1999; Young and Lai, 2004; Cleaver et al., 2011). The oscillation pattern of the plunging airfoil is very simple. So, the plunging airfoil has an advantage from the viewpoint of the practical use. Moreover, it was shown that the plunging airfoil can produce the lift and thrust forces under the condition of a certain amplitude and frequency (Cleaver et al., 2011). We can easily understand the validity of the plunging airfoil from these considerations, but we cannot find the sufficient studies and there is much left to be studied hereafter.

It is clear that the airfoil geometry has a strong effect on the performance of the plunging airfoil. As the airfoil of the MAVs operates in a low Reynolds number region, it is easily expected that the optimal airfoil geometry will differ from the ones of the ordinary air vehicles. However, we cannot find the optimal geometry of the plunging airfoil in a low Reynolds number region. In the presents study, the influence of the airfoil geometry on the performance of the plunging ones was studied numerically. As the purpose of the present study is to provide the basic data to understand the role of the airfoil geometry on the performance of the plunging one, two airfoils with the simple geometries were used. Moreover, the numerical calculations were carried out under the condition of the laminar flow to obtain the data for the extremely small MAVs, which are expected to develop extensively in future. The details will be shown later.
The analysis on the plunging airfoil has a strong relation with the biomechanical studies on the flying or swimming animals, birds, fish and insects, which have been carried out actively in recent years (Sudo et al., 2001; Taylor, Nudds and Thomas, 2003; Rohr and Fish, 2004; Triantafyllou, Techet and Hover, 2004; Kitagawa, 2012). These studies clarified a great number of the important results and provided the notable suggestions for the development of MAVs. One of the most important results will be the characteristics of the Strouhal number. That is, it was shown that many flying or swimming animals, birds, fish and insects (42 species) possess almost the same Strouhal number (Taylor, Nudds and Thomas, 2003). The plunging airfoil can be recognized as a simple model of the flying or swimming animals, birds, fish and insects. For this reason, the present numerical calculations were carried out under the wide range of the Strouhal number and the results were considered from a biomechanical viewpoint, too.

2. Methods

Some airfoils with different geometries were studied until now as the ones for MAVs. Within these airfoils, the circular arc airfoil is worthy to attention (Tezuka, Sunada and Rinoie, 2008). The circular arc airfoil has a simple geometry. So, this airfoil has an advantage for the production. In addition, this airfoil has a wide range of applications and we can find this airfoil easily in many situations (for example, Matsusita, Shiratori and Fukutomi, 2002). However, very little literature is available for the characteristics of this airfoil. In the present study, we adopted the symmetric circular arc airfoils because of the oscillation pattern of the plunging airfoil. The schematic model of the present study and coordinate system are shown in Fig. 1. In this figure, the airfoil is set within the freestream flow and the freestream velocity \( U \) is a constant. To reveal the plunging motion, we set the coordinate components of the airfoil center at \((0, A\sin(2\pi t/T_0))\), where \( A \) is an amplitude, \( T_0 \) is a period and \( t \) is time. Moreover, we should note that the angle of attack \( \beta \) is kept constant while the plunging oscillation. The geometries of airfoils are shown in Fig. 2 and Table 1. In this figure and table, chord length \( l_c \) is used as a characteristic length. Two kinds of airfoils were used in the present study and the most remarkable difference of these airfoils was the thickness of the airfoil. That is, the maximum thickness of type A airfoil is three times of the maximum thickness of type B airfoil. Usually, the insects possess the very thin airfoils. So, we considered the influence of the airfoil thickness in the present study.

The purpose of the present study is to obtain the data for the extremely small MAVs, whose characteristic length is on the order of \( 10^{-2} \) m. For this reason, the numerical calculations were carried out under the small Reynolds number (laminar flow region) and the flow was assumed to be the two-dimensional and incompressible. These assumptions are easy to understand. The geometry of the present flow domain changes with time because of the plunging oscillation of the airfoil. So, the arbitrary Lagrangian-Eulerian (ALE) method (Hirt, Amsden and Cook, 1974; Nakamura, Murakami and Ogiwara, 2001; Alawadhi, 2013) was used. The basic equations can be written as

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \quad (1)
\]

\[
\rho \left( \frac{\partial u}{\partial t} + (u - \zeta) \frac{\partial u}{\partial x} + (v - \eta) \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \mu \nabla^2 u, \quad (2)
\]

\[
\rho \left( \frac{\partial v}{\partial t} + (u - \zeta) \frac{\partial v}{\partial x} + (v - \eta) \frac{\partial v}{\partial y} \right) = -\frac{\partial p}{\partial y} + \mu \nabla^2 v, \quad (3)
\]

where \((u, v)\) is the velocity components, \( p \) is the pressure, \((\zeta, \eta)\) is the grid velocity components, \( \rho \) is the density, \( \mu \) is the viscosity coefficient, and \( \nabla^2 \) is the two-dimensional Laplacian.

As the inlet boundary condition, uniform velocity \( U \) is imposed while the velocity component of \( y \)-axis is assumed zero. At the outlet, the free flow-out condition (for example, Ralph and Pedley, 1988) and zero pressure condition are imposed. The free flow-out condition can be used as the boundary conditions on the

![Fig. 1 Schematic model of plunging airfoil and coordinate system.](image)
upper and lower ends, too. In addition, the boundary condition at the airfoil surface can be determined by the no-slip condition. The finite element method was adopted to obtain the numerical results in the present study. The finite element method has the advantage over the finite difference method when solving the viscous flow in complex geometries. Moreover, the pressure and velocity distributions were obtained by using the SMAC method (Amsden and Harlow, 1970; Watanabe, 2008), and the discretized equations were solved by using the MICCG method (for example, Murata, Oguni and Karaki, 1985). In the present study, the numerical calculations were carried out within the range of $c_l x \leq -10^2$, $c_l y \leq 2 2$. The total number of grid points was about 55000, and we recognized that this mesh division was sufficient to reveal the detailed flow fields from the comparison of the calculated results with different grid points. Moreover, we found that the numerical calculation over 20 cycles was required to obtain the periodic solution. So, the discussion mentioned later was performed with respect to the results of 20th cycle.

3. Results and discussion

The present numerical results are characterized by the Reynolds number $Re$, Strouhal number $St$, non-dimensional amplitude of plunging oscillation $A/l_{c}$, angle of attack $\beta$, and the geometry of airfoil. The Reynolds number and Strouhal number are defined by

$$Re = \frac{\rho U l_c}{\mu}, \quad St = \frac{l_c}{U T_0}. \quad (4)$$

The purpose of the present study is to obtain the data for the extremely small MAVs. So, we set the values of the Reynolds number at 500 and set the non-dimensional amplitude at 0.1 after the suggestion by Cleaver et al. (2011). However, we changed the other factors to evaluate the influence of the Strouhal number, angle of attack and the geometry of airfoil. For this reason, the numerical calculations were carried out over 80 times.

At first, let us consider the distributions of the pressure and wall shear stress along the surface of the airfoil. The results are shown in Figs.3-10. In these figures, the results for $\beta = 15$ deg are shown as one example and the pressure coefficient $C_p$ is defined by

$$C_p = \frac{P - P_0}{\frac{1}{2} \rho U^2} \quad (5)$$

where $P_0$ is the pressure at the leading edge. In addition, $s$ is the coordinate along the chord and the condition of $s/l_c = 0$ or $s/l_c = 1.0$ shows the leading or trailing edges respectively. The value of $\beta$ was determined with reference to Cleaver et al. (2011). Figures 3-6 show the distributions of the pressure coefficient along the surface of the airfoil. These figures show that the Strouhal number has the strong effect on the pressure coefficient. In the present study, the plunging motion of the airfoil can be revealed by the sine curve as mentioned above. So, the upstroke phase is shown by $0 < t/T_0 < 0.25$, $0.75 < t/T_0 < 1$ and the downstroke phase is shown by $0.25 < t/T_0 < 0.75$. We cannot ignore the vertical component of the relative velocity to the airfoil in a high Strouhal number region. Therefore, it is easily expected that the pressure coefficient of the top surface becomes greater than the one of the bottom surface for the upstroke phase and the pressure coefficient of the bottom surface becomes greater than the one of the top surface for the downstroke phase in a high Strouhal number region. This consideration agrees with the results shown in Figs.4 and 6 qualitatively. In addition, these figures show that the geometry of the airfoil

| Table 1 Parameters to determine the airfoil geometry. |
|---------------------------------------------|
| type of airfoil | $\theta$ | $r_c$ | $h_m$ |
| type A         | 15 deg  | 1.932$l_c$ | 0.132$l_c$ |
| type B         | 5 deg   | 5.734$l_c$ | 0.044$l_c$ |

Fig. 2 Airfoil geometry
Calculated distributions of the pressure coefficient along the surface of the airfoil under the condition of $St=0.1$ and $\beta=15$ deg (airfoil: type A, - - - :top surface of the airfoil, --- :bottom surface of the airfoil).

Calculated distributions of the pressure coefficient along the surface of the airfoil under the condition of $St=2.0$ and $\beta=15$ deg (airfoil: type A, - - - :top surface of the airfoil, --- :bottom surface of the airfoil).

Calculated distributions of the pressure coefficient along the surface of the airfoil under the condition of $St=0.1$ and $\beta=15$ deg (airfoil: type B, - - - :top surface of the airfoil, --- :bottom surface of the airfoil).
Fig. 6 Calculated distributions of the pressure coefficient along the surface of the airfoil under the condition of $St=2.0$ and $\beta=15$ deg (airfoil: type B, $\cdots$: top surface of the airfoil, $\cdots$: bottom surface of the airfoil).

Fig. 7 Calculated distributions of the wall shear stress along the surface of the airfoil under the condition of $St=0.1$ and $\beta=15$ deg (airfoil: type A, $\cdots$: top surface of the airfoil, $\cdots$: bottom surface of the airfoil).

Fig. 8 Calculated distributions of the wall shear stress along the surface of the airfoil under the condition of $St=2.0$ and $\beta=15$ deg (airfoil: type A, $\cdots$: top surface of the airfoil, $\cdots$: bottom surface of the airfoil).
has the influence on the difference of pressure coefficient between the top surface and bottom surface. Figures 7-10 show the distributions of the wall shear stress. These figures show that the Strouhal number has the strong effect on the wall shear stress. The increase in the Strouhal number increases the vertical component of the relative velocity to the airfoil. The vertical component of the impinging flow will be divided into the forward flow and backward flow along the airfoil. Therefore, in a high Strouhal number region, the sign of the wall shear stress in vicinity of the leading edge will differ from the sign of the wall shear stress in vicinity of the trailing edge. These considerations agree with the results shown in Figs. 8 and 10. In addition, the geometry of the airfoil has the notable effects on the wall shear stress. That is, the airfoil of type B has an effect to promote the flow separation compared with the airfoil of type A in a low Strouhal number region (see Figs. 7 and 9). Moreover, the airfoil of type B has an effect to increase the wall shear stress near the trailing edge compared with the airfoil of type A in a high Strouhal number region (see Figs. 8 and 10).

From a practical viewpoint, the drag coefficient $C_d$ and the lift coefficient $C_l$ play the important roles in many situations. The calculated results are shown in Fig. 11. In this figure, the drag coefficient and the lift coefficient are defined by

$$D = C_d \cdot \frac{1}{2} \rho U^2 L, \quad L = C_l \cdot \frac{1}{2} \rho U^2 L,$$

where $D$ and $L$ are the drag force and lift force acting on the airfoil respectively. We should note the differences in the scale of $y$-axis for each panel. These forces can be calculated by using the distributions of the pressure and shear stress acting on the airfoil. From this figure, we can find that the result for $St = 0.1$ denotes the complicated

![Fig. 9](image1.png) Calculated distributions of the wall shear stress along the surface of the airfoil under the condition of $St=0.1$ and $\beta = 15$ deg (airfoil: type B, ---: top surface of the airfoil, ---: bottom surface of the airfoil).

![Fig. 10](image2.png) Calculated distributions of the wall shear stress along the surface of the airfoil under the condition of $St=2.0$ and $\beta = 15$ deg (airfoil: type B, ---: top surface of the airfoil, ---: bottom surface of the airfoil).
nature. However, this figure shows that the waveform of \( C_d \) and \( C_l \) approach to the sine curve with the increase in \( St \) or decrease in \( \beta \). This result holds true for the airfoils of type A and type B. It is clear that the complicated flow phenomena such as the occurrence of flow separation has a strong relation to the complicated nature of \( C_d \) and \( C_l \). So, it is expected that the increase in \( St \) has an effect to restrain the flow separation near the airfoil. This result means the validity of the high-frequency oscillation and does not conflict with the result of Cleaver et al. (2011).

Next, let us consider the normalized time when the thrust force or lift force takes a maximum value. Of course, the thrust force can be obtained by changing the sign of the drag force. The results are shown in Fig.12. In this figure, \((t/T_0)_{\max}^T \) or \((t/T_0)_{\max}^L \) is the normalized time when the thrust force or lift force takes a maximum value. This figure shows the violent change of these normalized times in the low Strouhal number region \(( St < 0.5 )\). Of course, this violent change can be explained by the complicated nature of \( C_d \) and \( C_l \) in a low Strouhal number region mentioned above. In a high Strouhal number region \(( St > 0.5 )\), the change of these normalized times become calm. Here, it should be noted that these normalized times increase generally with the increase in the Strouhal number. It is clear that the occurrence of the flow separation has an adverse effect on the generation of the thrust force and lift force. So, this result means that the increase in \( St \) has an effect to restrain the flow separation near the airfoil and does not conflict with the results mentioned above. The unsteady aerodynamic forces of the flapping small beetle \((Rhomborrhina japonica)\) were measured by Kitagawa (2012). He showed that the normalized time when the thrust force takes a maximum value lies near the end of the upstroke phase and the normalized time when the lift force takes a maximum value lies near the end of the downstroke phase. As mentioned above, the upstroke phase of the present study is shown by \( 0 < t < T_0 < 0.25 \), \( 0.75 < t < T_0 < 1 \) and downstroke phase is shown by \( 0.25 < t < T_0 < 0.75 \). So, the present result shows that the normalized time when the thrust force takes a maximum value lies near the middle of the upstroke phase and the normalized time when the lift force takes a maximum value lies near the beginning of the downstroke phase (see Fig.12). These facts suggest that the flapping of the small beetle \((Rhomborrhina japonica)\) can change the occurrence of the flow separation. However, the experimental conditions of Kitagawa (2012) differ remarkably from the present calculation conditions. That is, the Reynolds number and the Strouhal number of Kitagawa (2012) were about 1500 and 0.4 respectively. So, we cannot draw a conclusion. More detailed studies will be required in future.

The calculated time-averaged drag coefficient \( \overline{C_d} \) and the lift coefficient \( \overline{C_l} \), which play the important roles in many situations, are shown in Fig.13. From this figure, we can find that the increase in the Strouhal number (oscillation frequency) has an effect to increase the lift coefficient and decrease the drag coefficient. The increase in the angle of attack \( \beta \) has an effect to promote the flow separation and to decrease the lift coefficient. However, this figure shows that the plunging oscillation with the airfoil of type A and type B can obtain the lift force even if under the condition of \( \beta = 15 \text{ deg.} \) This result shows the validity of the high-frequency oscillation and is worthy to attention. Moreover, we can find that the airfoil of type A can produce the positive thrust force for both attack angles (10 deg and 15 deg) under the condition of a high Strouhal number. On the other hand, the airfoil of type B cannot produce the positive thrust force for the condition of \( \beta = 15 \text{ deg} \) within the present calculation conditions. These results can be explained by the fact that the airfoil of type B has an effect to increase the wall shear stress in a high Strouhal number region mentioned above.

It is well known that the drag force can be divided into two forces, that is, pressure drag force and frictional drag force. So, let us consider the relation of these two forces to understand the basic characteristics of the drag force more deeply. The results are shown in Table 2. In this table, \( \overline{D_p} \) and \( \overline{D_f} \) are time-averaged pressure drag force and time-averaged frictional drag force respectively. From this table, we can find that the increase in the Strouhal number has an effect to decrease the time-averaged frictional drag force. As shown above, the sign of the wall shear stress in vicinity of the leading edge differs from the sign of the wall shear stress in vicinity of the trailing edge in a high Strouhal number region because of the impinging flow from the vertical direction. For this region, we cannot find the sign of the frictional drag force and this value has a possibility to take the negative value for the case of the high Strouhal number. This consideration suggests that the frictional drag forces of this table are not so strange ones. On the other hand, this table shows that the pressure drag force has the complicated nature. In the majority of cases, the pressure drag force at \( St = 2.0 \) takes a small value compared with the one at \( St = 1.0 \). This result shows the meaning of the high-frequency oscillation. However, this result is not true for the case of type B and \( \beta = 15 \text{ deg.} \) This fact suggests that the flow pattern around the type B airfoil is strongly affected by the angle of attack, which does
not conflict with the results mentioned above.

Next, let us consider the efficiency for thrust force $\eta_1$. This value will play an important role if the production of the thrust force is taken a serious view. We can obtain this value by using the following equation (see Triantafyllou, Techet and Hower, 2004)

$$\eta = \frac{\bar{D} \cdot U}{P_m}$$

(7)

where $\bar{D}$ is the time-averaged drag force and $P_m$ is the time-averaged power required for the plunging oscillation. The value of $P_m$ can be calculated easily by

$$P_m = \frac{1}{T_0} \int_0^{T_0} (-L) \cdot w dt , \quad w = \frac{d}{dt} \left\{ A \sin \left( \frac{2\pi t}{T_0} \right) \right\} = \frac{2\pi A}{T_0} \cos \left( \frac{2\pi t}{T_0} \right).$$

(8)

The calculated results are shown in Fig.14. As we could not obtain the positive thrust force under the condition of $\beta = 15$ deg and type B airfoil, the results for this condition were omitted here. From this figure, we can find that the geometry of airfoil has a strong effect on the efficiency for thrust force. Moreover, we can find that the angle of attack does not have a strong effect on the efficiency of type A airfoil. For the practical use of MAVs, it is easily expected that the attack angle may change suddenly due to the natural phenomena. So, this result for type A is worthy to attention and will have an important meaning in future. Moreover, this figure shows that the maximum efficiency for the thrust force is about 0.05. This value is not so high. However, it is clear that the plunging oscillation is not suitable to produce the thrust force. It should be evaluated that this simple oscillation can produce the above efficiency for the thrust force.

The Strouhal numbers of many flying or swimming animals, birds, fish and insects (42 species) were studied by Taylor, Nudds and Thomas (2003). Within these 42 species, the large animals such as the dolphins (Delphinidae) or the small insects such as the moths (Lepidoptera) were included. So, the Reynolds number of these animals, birds, fish and insects will extend over a wide range. As a result, they showed that the Strouhal numbers of these animals, bird, fish and insect satisfy the following relation.

![Fig. 11 Calculated drag coefficient and lift coefficient. The results for $St = 0.1$ denote the complicated nature and suggest the occurrence of the complicate flow phenomena such as the flow separation.](image-url)
where $St_{TNT}$ is the Strouhal number defined by Taylor, Nudds and Thomas (2003). As the characteristic length of the Strouhal number, they used the amplitude of oscillation. So, the relation between the present Strouhal number and their Strouhal number is given by $St = 10 \times St_{TNT}$. Therefore, their result can be rewritten as $2.0 \leq St \leq 4.0$. By considering this relation with the results of Figs. 13 and 14, we can find that the Strouhal numbers of many flying or swimming animals, birds, fish and insects lie the excellent condition to obtain the high lift coefficient and low drag coefficient. Moreover, if the airfoils of these animals, birds, fish and insects possess the resemble characteristics of type A airfoil, we can find that the Strouhal numbers of these animals, birds, fish and insects lie the excellent condition to obtain the high efficiency for the thrust force. It is clear that the present analysis have the remarkable difference from the flying or swimming conditions of these animals, birds, fish and insects. Moreover, the flow was assumed to be the two-dimensional. However, it was shown that the present results have the interesting connection with these flying or swimming animals, birds, fish and insects. So, it is expected that the present analysis will capture the essence of the flow fields near the flying or swimming animals, birds, fish and insects.

![Graph](image1)

**Fig. 12** Calculated normalized time when thrust force or lift force takes a maximum value. In the high Strouhal number region ($St > 0.5$), these normalized times increase generally with the increase in the Strouhal number.

![Graph](image2)

**Fig. 13** Calculated time-averaged drag coefficient and lift coefficient. In the high Strouhal number region, the airfoil of type A can produce the positive thrust force for both attack angles, but the airfoil of type B cannot produce the positive thrust force for the condition of $\beta = 15$ deg within the present calculation conditions.
The calculated velocity distributions in the wake of the plunging airfoils are shown in Figs. 15 and 16. These figures show the distributions for the $x$-component of the velocity vectors along the $y$-axis at $x/l_x = 1.5$. The angles of attack for Figs. 15 and 16 are 10 deg and 15 deg respectively. From these figures, we can find the remarkable decelerated region under the condition of $St = 0.1$. However, the accelerated region becomes noticeable with the increase in the Strouhal number. The negative drag coefficient in a high Strouhal number region can be explained by the flow acceleration and the law of the momentum conservation. In addition, we can find that the influence of the airfoil geometry becomes clear under the condition of $\beta = 15$ deg. That is, the velocity drop for type A airfoil in vicinity of $y/l_y = 0$ is remarkable compared with that for type B airfoil under the condition of $St = 0.1$ (see upper panel of Fig.16). And the velocity drop for type B airfoil in vicinity of $y/l_y = 1$ is remarkable compared with that for type A airfoil under the condition of $St = 2.0$ (see the lower panel of Fig.16). Of course, this pressure drop leads to the increase in the drag coefficient of the airfoil. The difference of the drag coefficient between the type A airfoil and type B airfoil in a high Strouhal number region can be explained by this consideration qualitatively.

### Table 2  Calculated time-averaged pressure drag force and time-averaged frictional drag force.

| (a) airfoil: type A, $\beta=10$ deg. | (b) airfoil: type A, $\beta=15$ deg. |
|--------------------------------|----------------------------------|
| $St$   | $\overline{D_p}/(pU^2l_y)$ | $\overline{D_f}/(pU^2l_y)$ | $\overline{D_p}/(pU^2l_y)$ | $\overline{D_f}/(pU^2l_y)$ |
| 0.1    | 4.99e-02          | 1.10e-01       | 8.87e-02          | 9.30e-02       |
| 1.0    | 6.04e-02          | 7.04e-02       | 1.49e-01          | 5.85e-02       |
| 2.0    | -1.41e-01         | -6.28e-02      | -2.21e-02         | -1.08e-01      |

| (c) airfoil: type B, $\beta=10$ deg. | (d) airfoil: type B, $\beta=15$ deg. |
|--------------------------------|----------------------------------|
| $St$   | $\overline{D_p}/(pU^2l_y)$ | $\overline{D_f}/(pU^2l_y)$ | $\overline{D_p}/(pU^2l_y)$ | $\overline{D_f}/(pU^2l_y)$ |
| 0.1    | 5.27e-02          | 9.14e-02       | 9.95e-02          | 7.98e-02       |
| 1.0    | 7.87e-02          | 3.55e-02       | 1.29e-01          | 2.58e-02       |
| 2.0    | 5.58e-02          | -2.08e-01      | 3.70e-01          | -1.83e-01      |

Fig. 14  Calculated efficiency for thrust force. As we could not obtain the positive thrust force under the condition of $\beta = 15$ deg and type B airfoil, the results for this condition were omitted here.
he accelerated region becomes noticeable with the increase in the Strouhal number. The influence of the airfoil geometry becomes clear under the condition of $\beta = 10$ deg. 

Fig. 15 Calculated distributions for the $x$-component of the velocity vectors along the $y$-axis under the condition of $\beta = 10$ deg. 

Fig. 16 Calculated distributions for the $x$-component of the velocity vectors along the $y$-axis under the condition of $\beta = 15$ deg. 

The influence of the airfoil geometry becomes clear under this condition.
4. Concluding remarks

A numerical analysis has been carried out to study the influence of the airfoil geometry on the performance of the plunging airfoil. The calculation results showed that the high-frequency oscillation has an effect to increase the lift coefficient and decrease the drag coefficient. This result suggests the important role of the high frequency oscillation and agrees with the existing studies on the high Reynolds number. Moreover, the calculation results showed that the performance of the thick airfoil is insensible to the change of the attack angle compared with the thin airfoil. In addition, the calculation results showed that the optimal design of the plunging airfoils has a strong relation to the flying or swimming animals, birds, fish and insects. This fact means the important role of the biomechanical considerations for the development of the micro air vehicles.

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